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SUMMARY OF COMMUNICATION AND NAVIGATION SYSTEMS DEGRADATION IN A NUCLEAR ENVIRONMENT

General Electric Company—TEMPO
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This handbook summarizes nuclear weapon effects on communication and navigation systems and provides information for determining if sophisticated analyses are required for system evaluation. It replaces DASA 2090.

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SUMMARY

Communication and navigation systems are vital for the command and control of strategic and tactical forces. Many of these systems rely on electromagnetic propagation through the atmosphere, and they can be degraded by nuclear explosions that modify the atmosphere and produce electromagnetic radiation that interferes with desired signals.

Communication and navigation systems operate over a large portion of the electromagnetic spectrum (from tens of hertz to tens of gigahertz), and depending on frequency are very differently affected by both the natural and nuclear-disturbed atmospheric environments. The spatial and temporal variations in nuclear-disturbed environments are also large, varying from a fraction of a kilometer to thousands of kilometers and from a few seconds to many hours. The analysis of system performance generally requires detailed specification of the system mission and the nuclear weapon scenario, in addition to descriptions of system geometry, frequency, modulation, etc.

Systems operating below about 30 MHZ rely on the natural ionosphere for long-distance communications. They are susceptible to weapon effects, and system performance can be degraded or disrupted (generally by signal attenuation) for hours. Generally, widespread effects produced by multiple dispersed low-altitude bursts or by a few high-altitude bursts are required to disrupt system performance. Propagation below about 50 kHz is less affected than propagation at higher frequencies and is used for broadcast of low-data-rate high-priority messages.

Systems operating above 30 MHz generally use line-of-sight (LOS) propagation between transmitter and receiver terminals. Nuclear weapon effects include signal attenuation and a variety of phase effects that result in signal distortion. Typically, degradation regions affecting propagation above a few hundred megahertz are tens to hundreds of kilometers in extent, and the duration of effects is tens of seconds to tens of minutes for attenuation and from a few minutes to up to a few hours for signal distortion. Most of the propagation effects decrease with increasing frequency, so that degradation of propagation at higher frequencies generally occurs over a smaller region and is less persistent than degradation of propagation at lower frequencies (an exception is attenuation caused by dust lofted into the atmosphere by surface bursts).

Prediction of weapon effects is based on nuclear tests, laboratory experiments, theoretical studies, and simulation with certain atmospheric phenomena. Reasonably high confidence predictions can be made for most effects caused by bursts detonated below about 100 km. Prediction uncertainties increase with increasing burst altitude above 100 km, but many of the effects can be bounded with moderate confidence. Predictions for interacting, multiple, high-altitude detonations are incomplete.

PREFACE

This handbook replaces DASA 2090, which was prepared in 1968 to summarize results of a DNA-sponsored program to determine and describe communication link performance in nuclear environments. The current handbook is based on DNA and DOD reports listed in the Bibliography and presentations made at the DNA Longwave Workshop held at DNA 13-14 February 1979, the DNA/LASL High Altitude Summer Study held at LASL 8-25 August 1978, the DNA Symposium on Alternate Communication Concepts held at BDM Corporation 23-24 May 1978, and the AFWL Workshop on Nuclear Effects Vulnerability of Future MILSATCOM Links held at RDA 18-19 May 1977. Published workshop proceedings are listed in the Bibliography; others are in preparation.

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SECTION 1

INTRODUCTION

1.1 OBJECTIVES

Communication and navigation systems are vital for the command and control of strategic and tactical forces. Many of these systems rely on electromagnetic propagation through the atmosphere. Nuclear explosions can degrade system performance by affecting the propagation medium and by producing electromagnetic radiation that can be received as noise. This handbook provides an overview of weapon effects on communication and navigation systems and information for determining if sophisticated analyses are required for system evaluation. Nuclear effects on system material are not described.

Introductory descriptions of communication and navigation systems and nuclear weapon scenarios that can affect these systems are given in Sections 1.2 and 1.3. Summary descriptions of propagation in ambient and disturbed environments are given in Sections 2 and 3 for ionospheric-dependent propagation, in Section 4 for line-of-sight propagation, and in Sections 5 and 6 for scatter propagation.

1.2 COMMUNICATION AND NAVIGATION SYSTEMS

1.2.1 General

A communication system provides the information flow required in support of a particular mission. The system may consist of a number of nodes, with pairs of nodes connected by a communication link. Communication links in a system may use the same frequency band or operate in different frequency bands.

Figure 1-1 illustrates the analysis required to determine communication systems performance. The system description must be specified in terms of link definitions and system objectives, and the nuclear threat in terms of weapon characteristics, burst locations, and times. Often the detailed description of the threat is not known, and either parametric studies or attempts at bounding the threat are made. The analysis of link performance includes physical damage of terminals including EMP, TREE, and SGEMP as well as blast and thermal effects, and analysis of signal and noise propagation. If jamming increases noise levels, these noise sources must be included in the analysis to determine combined effects. After the performance of each link has been determined, a network analysis may be required to determine system performance if terminals are connected by many links.

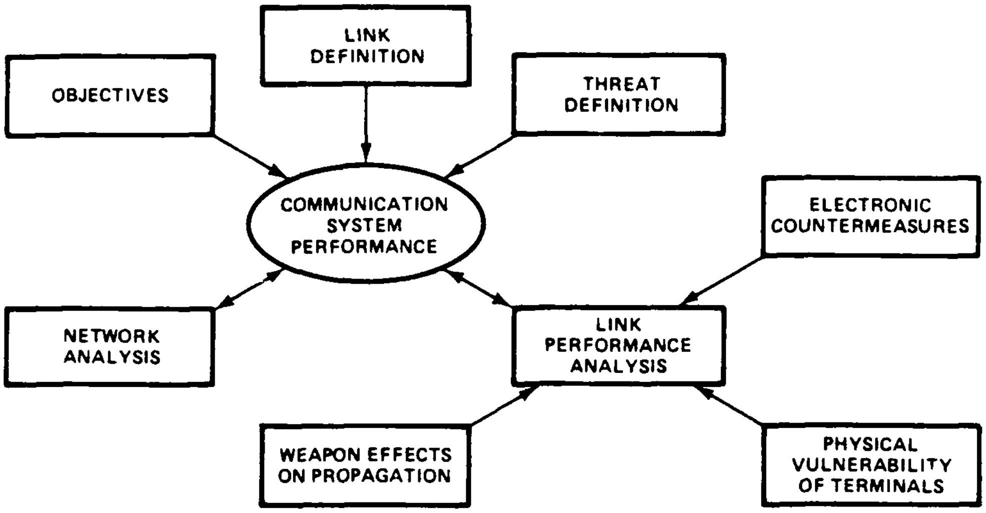

Figure 1-1 Communication system performance analysis requirements.

1.2.2 Communication Systems

Communication and navigation systems operate over a large portion of the electromagnetic spectrum. Table 1-1 shows frequency bands used, modes of propagation, and principal operational use. Communication systems operating in nuclear-disturbed environments can be described in terms of their use in strategic, tactical, and ballistic missile defense missions.

1.2.2.1 Strategic Communications

Table 1-1. Communication and navigation system frequency utilization.

Frequency Band and Range	Propagation Mode	Operational Use
ELF (extremely low frequency) 10 Hz to 100 Hz	Waveguide mode	Low-data-rate broadcast transmissions over long distances.
VLF (very low frequency) 3 kHz to 30 kHz	Waveguide mode	Same as above and navigation.
LF (low frequency) 30 kHz to 300 kHz	Groundwave and skywaves	Same as above and navigation.
MF (medium frequency) 300 kHz to 3 MHz	Groundwave and skywaves	Commercial broadcast over ground-wave distances.
HF (high frequency) 3 MHz to 30 MHz	Groundwave and skywaves	Medium-data-rate, two-way transmissions over long distances.
VHF (very high frequency) 30 MHz to 300 MHz	Line-of-sight (LOS), ionospheric, and meteor scatter	Medium to high data rate satellite, aircraft, and point-to-point LOS propagation. Low data rate beyond the horizon scatter links.
UHF (ultra high frequency) 300 MHz to 3 GHz	LOS, tropospheric scatter	High-data-rate satellite, aircraft, rocket probe, and point-to-point LOS propagation. Medium data rate beyond the horizon scatter links.
SHF (super high frequency) 3 GHz to 30 GHz	LOS	High-data-rate satellite, aircraft, rocket probe, and point-to-point LOS propagation.
EHF (extremely high frequency) 30 GHz to 300 GHz	LOS	High-data-rate satellite, aircraft, rocket probe, and point-to-point LOS propagation.

Figure 1-2 Current MEECN elements

Atlantic/Mediterranean area. Other communications being considered for an advanced MEECN include adaptive HF and meteor burst propagation.

1.2.2.2 Tactical Communications. Communications used for tactical missions include HF propagation (groundwave and skywave), UHF line-of-sight propagation, and troposcatter propagation. Future plans include the use of satellite systems to provide increased mobility and reliability. Line-of-sight propagation is used for short distances between ground terminals and between ground terminals and aircraft. Troposcatter propagation is used for propagation beyond line-of-sight distances. HF propagation is used for short-range communication (groundwave), and long-haul communication (skywave) to rear areas and the Defense Communication System. HF is also vital in establishing troposcatter links and is the backup communication system.

1.2.2.3 Ballistic Missile Defense Communication. Ballistic missile defense systems have stringent requirements for transmission of information to launch and control interceptors. This includes transmissions from control locations to sites where detection, acquisition, and tracking are performed and between control locations and interceptors. Typically, line-of-sight propagation of frequencies in the UHF and SHF bands is used.

1.2.3 Navigation Systems

Current long-range navigation systems include Loran, Omega, and Transit. A new satellite navigation system, NAVSTAR Global Positioning System (GPS), is being developed for use in the 1980's.

1.2.3.1 OMEGA. Omega is a VLF navigation aid. When fully operational, the OMEGA system will consist of eight ground-based transmitting stations located around the world that operate in the 10- to 14-kHz region. Any three stations can be utilized to form a grid using conventional phase-difference measurement techniques. Position accuracy within several kilometers can be obtained (differential measurements can be used to improve accuracy near reference stations).

1.2.3.2 LORAN. Loran-A is an MF navigation aid that is being replaced with OMEGA for military use. Loran-A uses pulse transmissions between 1.85 MHz to 1.95 MHz with a conventional master/slave configuration to establish time difference lines of position. Position accuracy is several kilometers for groundwave signals and about ten kilometers for skywave signals.

Loran-C is an LF navigation aid that uses a carrier phase comparison between master/slave stations and a time difference between pulse envelopes. Position accuracies of less than a kilometer can be obtained from the groundwave.

1.2.3.3 TRANSIT. Transit is a satellite navigation system that provides worldwide coverage. The system nominally consists of four satellites in polar orbit that continuously transmit ephemeris information on 150 and 400 MHz. A position relative to a satellite is determined from the doppler frequency of the received signal. Position can be determined at intervals of approximately 110 minutes or less depending on the general location. Position accuracy of several hundred meters can be obtained using one frequency, and accuracies within about 100 meters can be obtained using both frequencies to reduce errors introduced by ionospheric time delay.

1.2.3.4 GPS. The GPS will consist of twenty-four satellites positioned so that a minimum of six satellites will be visible at any time from any place on the earth's surface. Measurements by ground-based stations will precisely locate every satellite, and this information plus data on the satellite time reference and universal GPS time base is transmitted by the satellites. Measurements of the propagation time from four satellites (four measurements allow use of a relatively simple clock at the receiving site) provide position accuracies within a few meters. The GPS signal will be transmitted on two frequencies, one nominally centered at 1.575 GHz and the other nominally centered at 1.230 GHz. Several GPS user classes are planned related to different performance requirements. High-performance users will receive both frequencies to reduce errors introduced by ionospheric time delay and will utilize special signal modulation to obtain a secure, precision, anti-jam, and multipath resistant signal

1.3 WEAPON ENVIRONMENTS

1.3.1 General

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The following paragraphs describe nuclear bursts that may be used in strategic and tactical warfare and as an anti-communication tactic. Also described are two idealized weapon-produced environments often used in analysis of D-region effects. A tutorial description of propagation environments produced by nuclear bursts and resulting propagation effects is given in the appendix.

1.3.3 Ballistic Missile Defense

Offensive forces may use nuclear explosions as penetration aids against ballistic missile defense systems, and defensive systems may use a variety of weapon yields for reentry vehicle (RV) kill. Various detonation altitudes have been considered, depending on the nature of the postulated offense or defense.

Multimegaton weapons detonated between tens of kilometers and hundreds of kilometers are representative of interceptor and penetration aid weapons considered in area defense system studies. These weapons may be fired in barrages for either penetration or defense. Successive barrages can result in tens of detonations.

Interceptor weapons are designed to minimize degradation to the defensive radar systems, while the opposite is true for the penetration aid bursts. For some attacks, penetration aid weapons may be detonated at dispersed locations, resulting in widely spread fission debris at late times.

1.3.4 Tactical Weapons

Tactical weapons generally have yields of a few kilotons and would be detonated on or near the earth's surface. Weapon yields from less than a kiloton to a few hundred kilotons may be considered in tactical studies.

1.3.7 Idealized Weapon-Produced Environments

It is convenient and useful to specify two idealized D-region ionization environments produced by nuclear weapons for use in evaluating communication link performance. One is an environment representing the transient decay of ionization produced by prompt radiation, and the other is an environment representing the continuing ionization produced by delayed radiation. For communication links operating in and below the HF band, the idealized environments are primarily useful when the ionization is essentially uniform between the transmitter and receiver. For higher frequencies, the idealized environments are useful when they describe conditions where the propagation path traverses the D-region.

1.3.7.1 Ionization Impulse Environment. For bursts detonated above several hundred kilometers, prompt radiation produces widespread, D-region ionization at the time of the burst (see Figure 1-3). By a few tens of seconds after burst, the ionization is relatively independent of burst yield and altitude and is essentially determined by atmospheric species reactions. An idealized prompt radiation environment can be defined by evaluating prompt ionization for times after burst when the ionization is independent of initial conditions. For these conditions, the ionization at each altitude is only a function of time after burst and atmospheric parameters (species reaction rate coefficients).

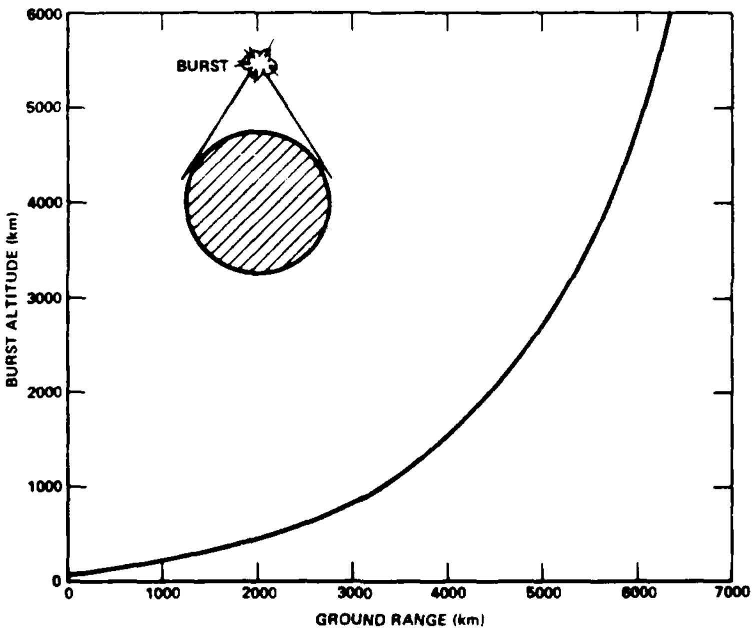

Figure 1-3. Extent of prompt ionization.

1.3.7.2 Spread Debris Environment. D-region ionization caused by delayed radiation from the fission debris can be simply modeled when the debris is above about 80 km and is uniformly distributed. For these conditions, the ionization in the D-region beneath the debris is due to beta particles and gamma rays and can be scaled in terms of the fission yield per unit area and average age of the debris. The spread debris scaling parameter w is defined by

$$w = \frac{W_F}{At^{1.2}} \qquad MT\ km^{-2}\ s^{-1} \quad ,$$

where

W_F = fission yield (MT)

A = debris area (km^2)

t = average age of debris (s).

Values of w/W_F versus time for several debris radii are shown in Figure 1-4. Values of w greater than 10^{-8} represent severe attack environments. Values of w between 10^{-9} and 10^{-12} are representative of a wide range of attack conditions and can occur over a considerable area even for relatively light attacks. For example, 15 MT of fission debris distributed over a circular area with a radius of 1500 km produces a value of w of 10^{-10} MT km^{-2} s^{-1}, one hour after burst (or bursts if more than one).

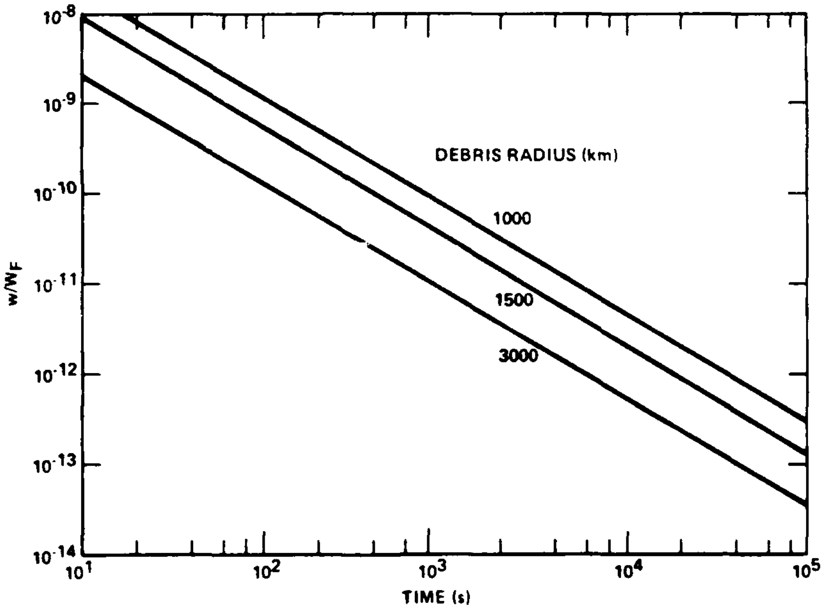

Figure 1-4. Spread debris parameter.

1.4 STATE OF KNOWLEDGE

The current knowledge of nuclear effects on EM wave propagation stems from nuclear tests, laboratory experiments, theoretical studies, and simulation with certain atmospheric phenomena. For bursts below about 30 km, system performance calculations can be predicted with high confidence. Exceptions are the dust environment produced by large-yield surface barrages and the late-time (hours) fission debris radiation environment. Predictions of dust distributions are quite uncertain. At late times the fission debris distribution is largely determined by atmospheric winds which can have considerable variation from nominal models.

For bursts between 30 and about 100 km, most phenomenology can be predicted with high confidence. Exceptions in this burst region involve detailed predictions of the structure of the beta particle ionization region and the late-time fission debris distributions. However, most of the system effects of interest can be bounded with good confidence.

As the burst altitude is increased above 100 km, predictions of nuclear phenomenology and effects on system performance become increasingly difficult. For bursts between 100 and about 300 km, the mean characteristics of the burst-produced electron density can be predicted with moderate confidence. Deficiencies in observational data and theoretical work make detailed predictions of the electron density structure difficult. Experimental programs such as the Air Force Geophysics Laboratory's Global Ionospheric Measurements, the DNA Wideband Satellite, and the DNA-Air Force STRESS Barium Release Tests are improving prediction confidence.

Environment predictions for bursts detonated above 300 km are of low confidence due to uncertainties associated with the details of weapon disassembly and subsequent asymmetries in energy release. However, many effects may be bounded with moderate confidence.

The preceding comments apply to single bursts, and to multiple bursts detonated below about 50 km. Predictions of environments resulting from interacting, multiple, high-altitude detonations are currently incomplete.

SECTION 2

ELF, VLF, AND LF PROPAGATION

2.1 GENERAL

Extremely low frequency (ELF), very low frequency (VLF), and low frequency (LF) radio waves are, in general, characterized by propagation reliability and both amplitude and phase stability when compared with high frequency radio waves. While the bandwidth and thus the information capability is relatively small, longwave propagation is used for communication and navigation systems which must operate over large distances with high reliability.

Communication systems operating in the upper VLF band and lower LF band are an essential part of the current MEECN system, and the Navy has actively pursued the development of an ELF system (SEAFARER) for essential communications. Because of the high transmitter power and large transmitter antenna requirement for long-range communications, systems using longwave propagation generally operate in the broadcast mode providing one-way communications.

2.2 PROPAGATION IN THE NATURAL ENVIRONMENT

At ELF and VLF the distance between the earth and the ionosphere is less than a few wavelengths and one can consider these as the boundaries of a waveguide. The received field strength is the sum of the normal modes that have propagated to the observation point. The quantities of interest are the excitation factor (the relative energy supplied to the mode by the transmitter), the attenuation rate (loss of energy per unit distance), and the phase velocity of each mode. In the daytime the energy is reflected from about 60-km altitude and at night from about 90 km. At night the orientation of the propagating wave with the geomagnetic field is significant, while for daytime (and for nuclear environments) the higher air density at the reflection altitude reduces this dependence. Propagation is affected by ground conductivity particularly at high latitudes, where conductivities less than 10^{-3} mhos m^{-1} are encountered.

ELF energy is transmitted and received as a single TEM mode, and VLF energy is generally transmitted and received as one or more TM modes. For VLF airborne terminals with large trailing wire antennas, propagation of TE fields must be considered and conversion of energy between TE and TM fields at the upper waveguide boundary (geomagnetic field effects) can be important.

For frequencies above 30 kHz, the distance between the earth and the ionosphere is many wavelengths. While the received field strength can be computed as the sum of waveguide modes, it usually is computed as the sum of the direct (or ground) wave, the first hop skywave (energy reflected once from the ionosphere), the second hop skywave (energy reflected twice from the ionosphere), etc.

VLF and LF groundwave propagation goes to considerable distances (up to several thousand kilometers) and generally represents a minimum signal for very disturbed conditions where the ionosphere does not reflect energy. Signal strengths less than the groundwave may occur for depressed ionospheres over regions of low ground conductivity, particularly in the VLF band.

Low-frequency noise is due to noise propagated from distant thunderstorm activity, local thunderstorm activity, and man-made noise. When the dominant noise source is distant atmospherics, the noise as well as the signal can be affected by burst-produced ionization. The signal-to-noise ratio may remain the same (signal and noise attenuated the same), may increase (signal attenuated less than noise), or may decrease (signal attenuated more than noise) depending on the relative geometry of the signal and noise sources, the receiver terminal, and the burst-produced ionization. When the received noise is determined by local noise (as is commonly the case), the noise is not affected by burst-produced ionization and the signal-to-noise ratio is determined by changes in the signal strength.

2.3 PROPAGATION IN A NUCLEAR ENVIRONMENT

2.3.1 General

A nuclear detonation increases the ionization in and below the D-region, which constitutes the top of the earth-ionosphere waveguide. The increased ionization may cause the following changes:

1. The reflection region may be lowered (ie, the top of the waveguide may be depressed)
2. The reflection characteristics of the upper boundary of the waveguide may be modified
3. An absorption region may be formed below the upper boundary.

In general, these changes will increase the attenuation rate. Lowering the reflection height can increase the excitation factor (amount of energy propagated) of the dominant mode, and the received signal strength will depend on the trade-off between attenuation and excitation. Changes in the reflection altitude also affect signal phase. Immediately after a burst the reflection altitude is rapidly lowered and the signal phase may change thousands of degrees in a few milliseconds. Following this, the ionosphere slowly recovers and phase changes of a few degrees per minute may be experienced. For most systems (particularly those with differential phase measurements) the phase changes following the initial change can be tolerated.

Degradation of long-wavelength systems normally will not be significant unless a large portion (greater than several hundred kilometers) of the path between transmitter and receiver terminals is affected. An ionization impulse resulting from a very high altitude (even though low yield) detonation affects a wide area and may degrade system performance for tens of minutes. Following multiple dispersed bursts or at late times after a single high-altitude burst, fission debris can produce widespread ionization that affects long-wavelength systems for tens of minutes to hours. Examples of propagation effects for conditions approximating these widespread ionization environments (see Section 1.3.7) are given below.

2.3.2 Ionization Impulse Environment

Figure 2-1 shows the vertical electric field strength for a 4000 km link in the idealized ionization impulse environment described in Section 1.3.7.1. For bursts detonated above about 1000 km, prompt ionization can modify the ionosphere over the entire link (see Figure 1-3). As mentioned in Section 1.3.7.1, the

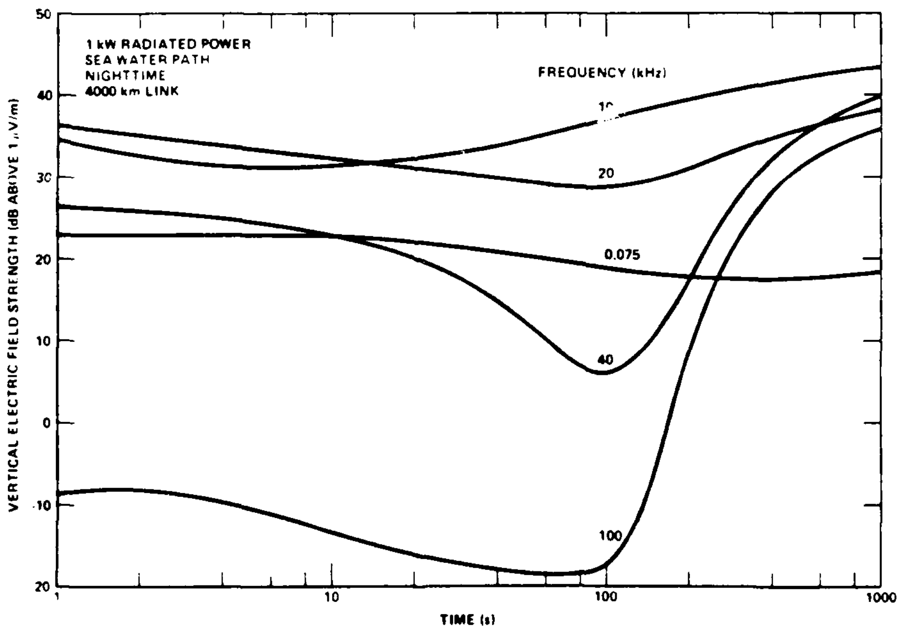

Figure 2-1. Signal strength for prompt radiation environment.

ionization after a few tens of seconds is essentially independent of weapon yield, and relatively small (fraction of a megaton) yield bursts can produce effects similar to those shown in Figure 2-1. The results shown in Figure 2-1 are for a vertical electric dipole transmitter antenna except for ELF, where a horizontal dipole antenna over poorly conducting soil (1.7×10^{-4} mhos/m) was assumed.

The signal loss is significant for several minutes and is larger at the higher frequencies. The calculations shown in Figure 2-1 are for uniform ionization over the entire path. For longer links or links where the burst-produced ionization is largely between the terminals, the change in attenuation will dominate changes in the excitation factors and the electric field strength will be less than is shown in Figure 2-1.

Similar results are obtained for daytime conditions, except recovery of the signal strength to ambient occurs somewhat faster. VLF and LF TE propagation (elevated horizontally polarized transmitting antenna) will be attenuated more by nuclear-weapon-produced ionization than TM propagation. Predictions of propagation effects caused by prompt radiation are uncertain mainly due to uncertainties in atmospheric chemistry. The uncertainties can be approximately accounted for by allowing for a factor of three in the time when the signal strength recovers to a given value.

2.3.3 Spread Debris Environment

Figure 2-2 shows vertical electric field strength for a 4000 km link in the idealized spread debris environment described in Section 1.3.7.2. For this intermediate-length link, values of the spread debris parameter, w, greater than about 10^{-10} MT km^{-2} s^{-1} can produce significant reductions in VLF signal strength, while somewhat smaller values can affect LF signals.

As previously mentioned, the change in signal strength is due to the combined changes in excitation factors and attenuation rate, and effects will vary depending on the relative location of the burst-produced ionization and the link terminals. The dashed curve in Figure 2-2 shows electric field strength when the ambient excitation factors are used; comparison of this curve with the solid curve shows the importance of the excitation factors when the regions above the terminals are affected and the link is relatively short. As for prompt radiation, TE propagation is affected more than TM propagation. Similar results are obtained for daytime conditions.

Ionization is produced in the burst region and in the geomagnetic conjugate of the burst region. Uncertainties in the predicted electric field strength

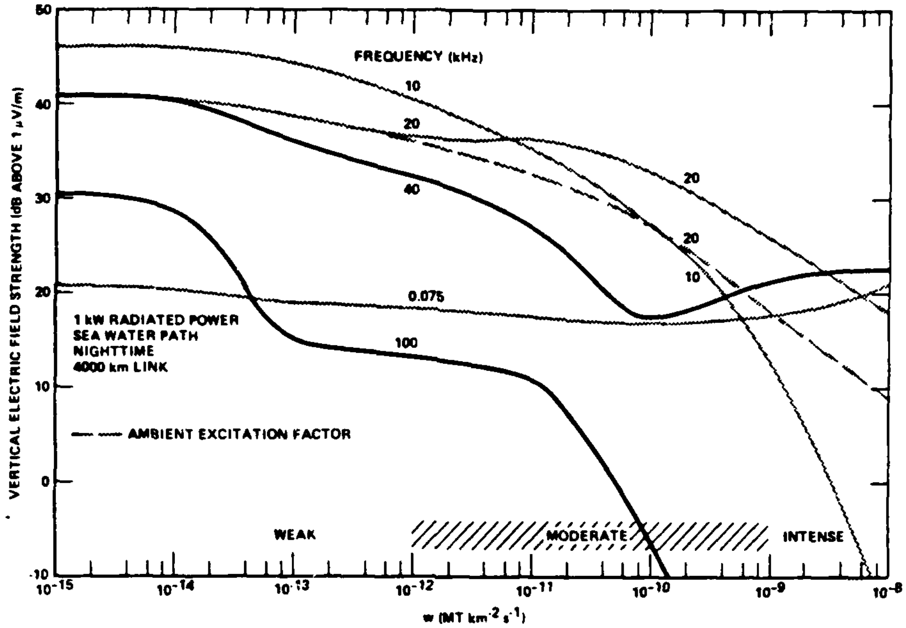

Figure 2-2. Signal strength for spread debris environment.

depend on a number of factors, including frequency, magnitude of ionization, and link length, and are difficult to generalize. For a 4000 km link and moderate ionization levels, the predicted field strengths are uncertain by about a factor of three (largely due to uncertainties in atmospheric chemistry and ion-neutral collision frequencies). This is comparable to that caused by uncertainty in specifying the appropriate value of the spread debris parameter, which depends on burst scenario and late-time debris modeling.

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SECTION 3

MF AND HF PROPAGATION

3.1 GENERAL

The HF band is used to support both strategic and tactical operations. Strategic communications typically use long-distance links (greater than several thousand kilometers), while tactical communications typically use links of a few hundred to several thousand kilometers. Long-distance HF links may constitute a major part of the U.S. post-attack communication capability. The MF band is generally limited to groundwave propagation and is mainly used for commercial broadcasts.

The principal HF systems used are voice and frequency shift keying (FSK). For many applications, voice quality is a function of only the signal-to-noise ratio, and time and frequency distortions of the signal can be neglected. A signal is generally usable if the signal-to-noise ratio exceeds a threshold of 20 to 30 dB.

Development of adaptive HF circuits that can rapidly select optimum propagation frequencies including frequencies in the lower VHF band is being considered to improve operation in the post-attack period. Use of MF groundwave propagation to connect terminals in a communication grid is also being studied for use in the trans- and post-attack periods.

3.2 PROPAGATION IN THE NATURAL ENVIRONMENT

HF line-of-sight (LOS) and groundwave propagation are used for short-range communications, particularly for tactical communications. The range of the groundwave depends on terrain, conductivity, and propagation frequency and can be as much as several hundred kilometers.

For long distances the HF signal is propagated by many skywaves connecting transmitter and receiver, each traveling via the ionosphere with a different geometry. Figure 3-1 shows an example of the skywave geometry of a 4000-km path during the daytime at a single frequency. This multi-ray path characteristic of HF is very important in any analysis of the susceptibility of a circuit to degradation from nuclear effects. Natural variations in the ionosphere affect the ray-path geometry at any specific time.

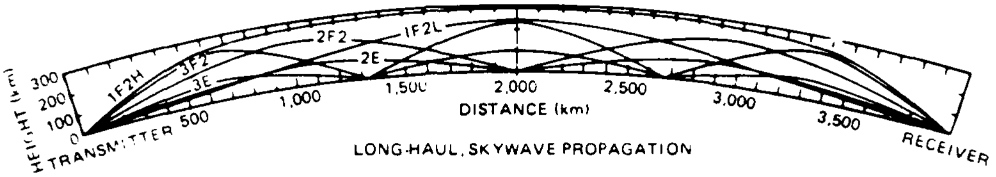


Figure 3-1. Example of HF ray-path geometry.

Two regions or segments of a skywave are critical to its usefulness for communication. The first is the region of reflection. A proper combination of electron density and incidence angle is required before reflection is possible. Depending upon operating frequency, reflection normally occurs in the ionospheric E-region (90 to 150 km altitude) or F-region (>150 km). The second skywave segment of importance is that in the D-region (50 to 90 km). Because of the high collision frequency between neutral particles and electrons, this region is responsible for most of the absorption (loss of signal strength) incurred along a given ray. Little ray bending normally occurs in this region.

The usable frequency spectrum extends from the maximum usable frequency (MUF) down to the lowest frequency that provides acceptable signal quality. The maximum usable frequency is determined by the reflection region and is lower at night than in the daytime due to the smaller electron density at night. The lowest frequency is determined by signal strength and the received noise intensity (and signal distortion in the case of FSK). In the daytime, signal strength is reduced by D-region absorption and the lowest usable frequency is higher than at night, when D-region absorption nearly disappears. Examples of usable frequencies for several path lengths are shown in Table 3-1.

Table 3-1. Preburst propagating frequencies.

Path Length (km)	Usable Spectrum (MHz)	
	Day	Night
Long (8,000)	14-28	4-16
Intermediate (4,000)	8-28	2-16
Short (400)	4-8	2-5

Source: DASA 1955-1

While signal-to-noise ratios are generally greater at night than in the daytime, time delay dispersion is more significant. This results from signals being received from more than one skywave with nearly equal magnitudes but different propagation times (different path lengths). Time delay dispersions cause reduced signal bandwidths.

Received noise in the HF band has been calculated as a combination of propagated noise from thunderstorm centers (concentrated mostly in tropical areas) and man-made local noise. Atmospheric noise is the dominant type at night when ionospheric absorption is less, whereas man-made noise may set the daytime level. Very often, however, the noise level is determined by other interfering signals due to congestion of the HF band.

Normal propagation in the MF band is characterized by large attenuation of skywaves in the daytime, limiting communication to the groundwave range. At night skywave signals from other stations can cause interference.

3.3 PROPAGATION IN A NUCLEAR ENVIRONMENT

3.3.1 General

The nuclear environment can affect both the D-region and reflection region segments of the propagation path. Generally the dominant effect is absorption resulting from D-region ionization. The duration of absorption depends on weapon parameters, frequency, and time of day (day or night) and varies from a few minutes for a small-yield burst and nighttime conditions to several hours or more for a large-yield burst and daytime conditions.

Detailed calculations of signal attenuation due to D-region absorption require determining the absorption for each skywave connecting transmitter and receiver. Because D-region ionization does not appreciably alter preburst geometry, the preburst geometry often can be used in determining signal attenuation. However, as discussed below, burst-produced changes in E- and F-region electron densities can alter the number and location of skywaves and thus affect attenuation calculations.

Because of the multiple skywave characteristics of HF propagation, the absorption region must be relatively large to prevent signal propagation. Small absorption regions such as those produced by low-altitude bursts can affect signals, but the results are critically dependent on skywave geometry. In the HF band D-region absorption scales inversely with frequency squared and can be minimized by using frequencies as close to the MUF as possible. In some circumstances discussed below, propagation in the lower portion of the VHF band may be possible with consequent reduction in signal attenuation. Since a large fraction of HF noise may be propagated via the ionosphere, the received noise level can also be reduced by D-region absorption. Burst-produced D-region absorption may improve MF groundwave reception at night by attenuating interfering skywave signals. Generally the normal D-region absorption for daytime conditions will attenuate MF skywave signals.

Burst-produced ionization and traveling disturbances (shock waves, acoustic gravity waves) in the E- and F-regions of the ionosphere can produce significant changes in the reflection region ionization that can last for hours. For burst altitudes in and above the upper D-region, prompt radiation can produce widespread E- and F-region ionization, principally in the burst region but also in the geomagnetic conjugate region (opposite hemisphere). The region in which the air is initially singly ionized and highly heated (fireball region) can remain sufficiently ionized to reflect and scatter HF and VHF energy for hours after burst. Following the three highest Fish Bowl events VHF reflections from the fireball were observed on oblique ionospheric sounders for several hours after burst.

After a few minutes, high-altitude fireballs (plumes) are aligned along the geomagnetic field and become elongated tubes that can extend from one hemisphere to the other. Reflections from these late-time fireball regions may allow propagation in the VHF band when absorption is severe at lower frequencies. However, the usefulness of these burst-produced skywave paths (sometimes called bomb modes) depends critically on the relative geometry of transmitter, receiver, and fireball. Useful reflections may not be possible at mid- and high-latitudes. Nevertheless, systems able to utilize VHF propagation may be able to substantially reduce circuit outage times.

Large-scale traveling disturbances in the E- and F-regions of the ionosphere are coupled to the existing ionization and can cause either positive or negative perturbations in the electron density, depending upon height, velocity, wave propagation direction with respect to the geomagnetic field, and other parameters. For bursts above about 50 km, a strong shock wave may propagate in the F-region to considerable distances, affecting atmospheric density, composition, temperature, and ionization. Following Teak (a nighttime large-yield D-region burst), there was a large region (several thousand kilometers in diameter) in which the electron content in the F-region was diminished substantially below normal values until the following morning. The result was to lower the critical frequency and thus degrade or break HF communication links, depending on F-region reflections. Such severe changes in F-region reflection properties were not noted during the Fish Bowl test series; however, reductions of 50 percent lasting a few hours were noted.

F-region depletion is expected to be a significant degradation phenomenon near the burst after large-yield, nighttime, D-region detonations. Recovery of the F-region after daytime detonations is expected to occur more rapidly; however, it is not known whether there will be defocusing, multipath, and fading of HF signals reflected from the region.

As the shock wave propagates away from the source, it loses energy and evolves into acoustic gravity waves. These waves can propagate many thousands of kilometers and, depending on the direction of propagation relative to the geomagnetic field, either increase or decrease the maximum F-region electron density. Substantial increases in electron density and thus critical frequency (increases in critical frequency up to a factor of 3) that can be related to acoustic gravity waves were noted in the southern conjugate region following the Teak, King Fish, and Star Fish bursts.

3.3.2 Ionization Impulse Environment

Figure 3-2 shows the one-way vertical absorption produced by the idealized ionization impulse environment described in Section 1.3.7.1. For bursts detonated above about 1000 km, prompt ionization can affect both the upgoing and downgoing

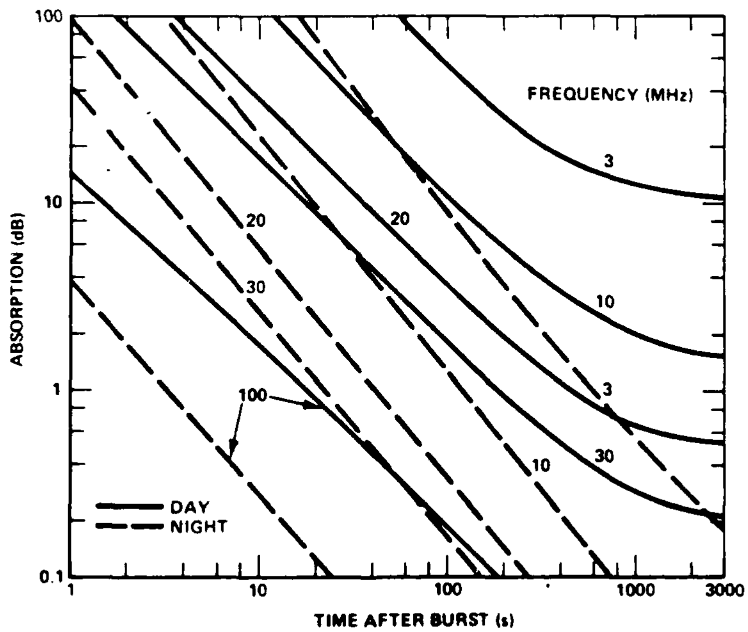


Figure 3-2. One-way vertical absorption due to prompt radiation.

segments of a skywave (see Figures 3-1 and 1-3). As mentioned in Section 1.3.7.1, the ionization after a few tens of seconds is essentially independent of yield, and relatively small (fraction of a megaton) yield bursts can produce effects similar to those shown in Figure 3-2.

For typical HF links the one-way path absorption is about 5 times the one-way vertical path absorption (angle of incidence in the D-region of about 80 degrees). Thus for widespread impulse environments that affect two or more D-region segments, the signal loss will be at least 10 times the one-way vertical path absorption and significant HF absorption can last for a few minutes in the daytime and a few tens of seconds at night. If VHF propagation can be utilized, the duration of significant absorption due to prompt radiation will be reduced to a few seconds.

Predictions of propagation effects caused by prompt radiation are uncertain mainly due to uncertainties in atmospheric chemistry. The uncertainties can be approximately accounted for by allowing for a factor of 3 in the time when the absorption reaches a given value.

3.3.3 Spread Debris Environment

Figure 3-3 shows one-way vertical absorption in the idealized spread debris environment described in Section 1.3.7.2. Values of the spread debris parameter, w, greater than about 10^{-12} MT km^{-2} s^{-1} can produce significant HF signal loss. If VHF propagation can be utilized, values of w greater than about 10^{-10} MT km^{-2} s^{-1} would be necessary to affect signal levels.

For a given value of w the prediction of absorption due to delayed radiation is uncertain by about a factor of 2, largely due to uncertainties in atmospheric chemistry. The appropriate value of w is uncertain due to uncertainties in the number, location, and parameters of bursts and at late times the fission debris distribution.

For debris above 80 km (assumption used in determining idealized spread debris environment), beta particles produce D-region ionization beneath the debris and at the geomagnetic conjugate region. Thus, for high-altitude debris regions there are two absorption regions: one on each side of the geomagnetic equator.

A large-scale ground attack can result in a widespread low-altitude debris region. Gamma radiation from the debris will produce D-region ionization in the burst locale. For debris dispersed at about 25 km altitude (approximate stabilization altitude for large-yield surface bursts), the one-way vertical absorption can be estimated by dividing the absorption obtained from Figure 3-2 by a factor of about 7. Thus, the one-way vertical absorption at 20 MHz for $w = 10^{-10}$ MT km^{-2} s^{-1} would be about 5 dB for daytime conditions.

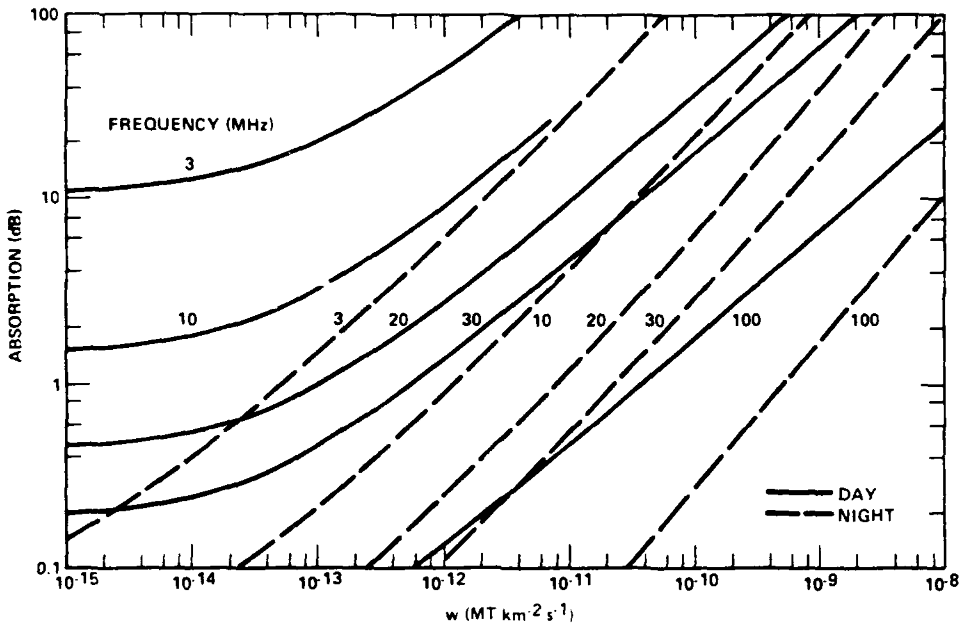


Figure 3-3. One-way vertical absorption due to delayed radiation.

and has range advantages (ie, reduced node numbers) over line-of-sight, ground-based networks. Such networks are well suited to serving a relatively localized set of subscribers.

2. Communication links dependent on skywave propagation are vulnerable to nuclear burst degradation. The major effects are D-region absorption and disturbances to skywave reflection regions (E- and F-regions).

3. Widespread effects lasting for hours can result from a massive lay-down of megaton surface bursts, a few large-yield bursts detonated between 50 and about 500 km, or smaller yield weapons detonated sequentially (few minute intervals) above several hundred kilometers.

4. The effects of a few bursts detonated below about 30 km generally will be negligible or short-lived unless the bursts are accurately placed. Burst location for single bursts detonated above 30 km can also be critical, depending on burst and link parameters and time of day (day or night). The duration of D-region absorption is much less at night than during the day.

6. Uncertainties in D-region absorption predictions are mainly due to uncertainties in atmospheric chemistry and the location of fission debris. Predictions of the location and extent of fission debris increase in uncertainty with increasing altitude and time. Predictions of disturbances to the normal reflection regions and the creation of new reflection regions are highly uncertain.

SECTION 4

LINE-OF-SIGHT PROPAGATION

4.1 GENERAL

4.2 PROPAGATION IN THE NATURAL ENVIRONMENT

Propagation in and above the UHF band is essentially not affected by the mean properties of the natural ionosphere. Scintillation effects related to ambient ionization inhomogenities at equatorial and polar locations may affect UHF and occasionally SHF propagation. Signal attenuation due to water vapor and molecular oxygen may be important when evaluating SHF and EHF propagation.

Generally system noise levels are determined by receiver input noise. Low-noise receivers may be used in commercial links, but are usually not considered for military applications since they increase the vulnerability to nuclear-burst-produced noise.

Typical modulation schemes for satellite communications include frequency-division multiplex frequency modulation (FDM-FM), and digital phase shift keying (PSK). PSK is being considered for use with systems employing time division multiple access (TDMA) and code division multiple access (CDMA) using spread spectrum techniques.

4.3 PROPAGATION IN A NUCLEAR ENVIRONMENT

4.3.1 General

The major effects caused by a nuclear environment are due to the creation of free electrons. The increased electron density results in absorption, refraction, time delays, dispersion, Faraday rotation, and noise. Inhomogeneities in electron density result in scintillation in amplitude, phase, angle of arrival, and propagation time delay. Propagation can also be affected by dust clouds caused by surface bursts. Molecular resonance absorption due to burst-produced species may be important in the EHF band.

Subionospheric propagation paths (paths entirely below about 50 km) generally will only be affected when the path goes through or very close to a fireball region or dust cloud. Transionospheric propagation paths can be affected when the path is in or close to a fireball or goes through burst-produced, D-region ionization. Traveling disturbances (shock waves, acoustic-gravity waves) may produce inhomogeneities in the ambient F-region ionization over thousands of kilometers, resulting in scintillation effects similar to those occurring during severe ambient cor ..ions. However, quantitative models for these potentially widespread, striated regions that could affect transionospheric propagation are incomplete.

Because of the relatively small size and rapid motion of fireballs for bursts below 100-km altitude, the duration of fireball effects is limited to the path interdiction time, typically tens of seconds. For higher altitude bursts, the fireball motion may not be sufficient to move the region out of the sight line to a synchronous satellite, and the degradation period may be extended to tens of minutes. For nonsynchronous satellites and probes the duration of effects generally will be determined by the motion of the propagation path.

The received noise level can be increased by thermal emissions from fireball regions. The fireball will remain at temperatures above about 1000 K from a few tens of seconds for low-altitude bursts to a few tens of minutes for high-altitude bursts, and can produce effective antenna noise temperatures of several thousand degrees if the antenna is pointed at the fireball. In general, thermal noise will be significant only for systems with low receiver noise temperatures. The actual noise received will depend on the properties of the fireball (whether it is absorbing at the frequency of interest), the amount of attenuation outside the fireball, and the directivity of the antenna.

D-region ionization produced by delayed radiation (beta particles, gamma rays) produces absorption that lasts from tens to hundreds of seconds depending on frequency, burst altitude, and fission yield. Delayed gamma rays can affect propagation in the VHF band over a region of several hundred kilometers in radius for tens of seconds. The extent of D-region absorption caused by beta particles is determined by the debris expansion and can affect propagation in the VHF and lower UHF bands for tens to hundreds of seconds.

Fireball regions are initially highly ionized. For fireballs below about 100 km, electron collisions with neutral particles cause absorption to be the dominant propagation effect due to burst-produced ionization. At higher altitudes, phase effects can continue to be important after absorption has diminished. For surface bursts, dust lofted by the fireball can produce a dust cloud within and below the fireball that scatters and attenuates electromagnetic energy.

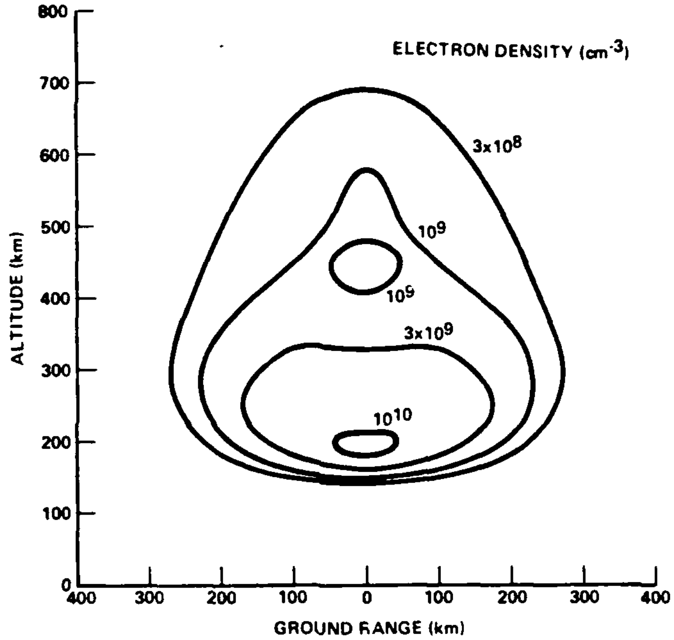
gure 4-1 shows the absorption caused by propagating through a fireball

Figure 4-1 Fireball absorption for a 1 MT surface burst and dust cloud produced by a 1 MT surface burst. For surface bursts the absorption due to electrons is essentially independent of frequency for propagation frequencies below about 10 GHz. The absorption due to the dust cloud is approximately proportional to frequency. The range in values shown is due to the effects of different soil types. Fireball and dust cloud regions for surface bursts are a few kilometers in radius during the first few minutes after burst. The absorption due to dust shown in Figure 4-1 is for a vertical path through the dust cloud. For horizontal paths both the magnitude and time history of absorption depend on path altitude. Propagation through dust clouds may also result in large amplitude and phase scintillations; however, quantitative models are incomplete. Figure 4-2 shows burst yield-altitude combinations producing dust effects.

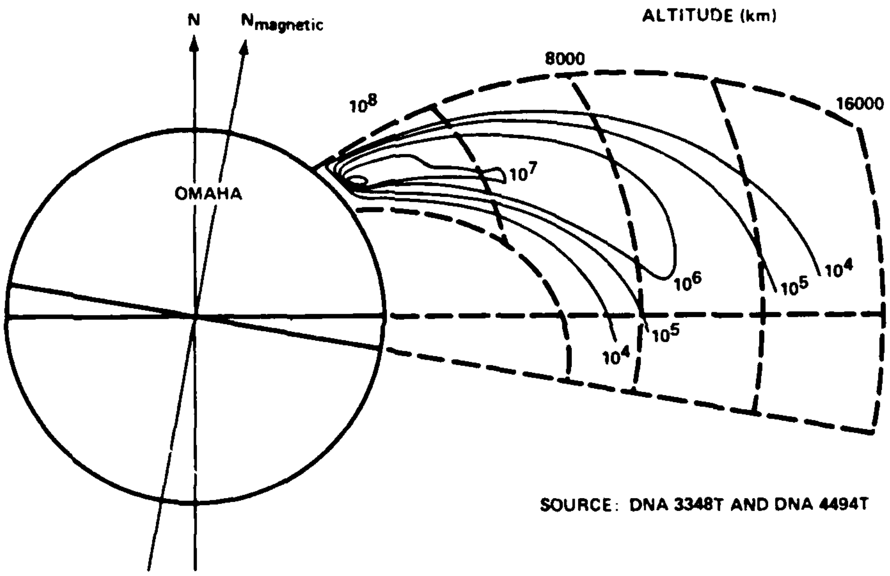
Figure 4-2 Yield-altitude region producing dust clouds

Figure 4-3 One-way path absorption through fireball for a 1 MT, 60 km burst

Fireball regions for bursts detonated above 100 km can be large and after a few tens of seconds become aligned along the geomagnetic field. Figure 4-4 shows predicted electron density contours after a large-yield burst at 200 km. The absorption and phase effects depend on the location of the propagation path within the fireball. The following figures are for paths near the bottom of the fireball that are nearly normal to the fireball axis.



(a) t = 30 s



(b) t = 2000 s

Figure 4-4. Electron density contours at 30 and 2000 seconds after a high-altitude burst.

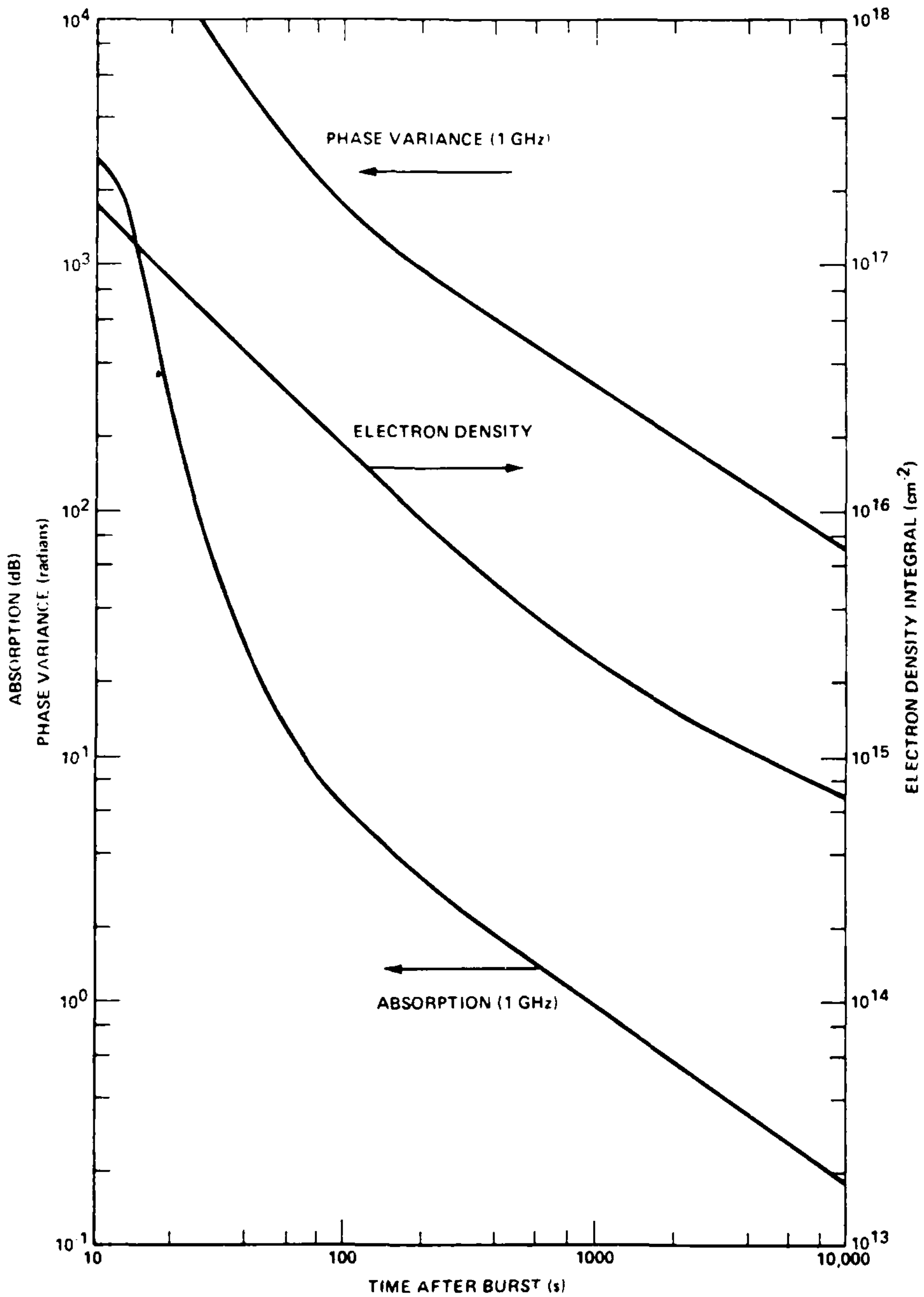


Figure 4-5. Propagation path integrals for a large-yield, 200-km burst.

Refraction is proportional to the integral of the gradient of electron density normal to the propagation path. Generally refraction will not be important for communication problems unless other effects are also important.

The large spatial region that can be affected by high-altitude fireballs is illustrated in Figure 4-6. This figure shows contours of the electron density integral 2000 seconds after a large-yield burst at 200 km for propagation paths between an equatorial, synchronous satellite and the ground.

After a few tens of seconds the fireball ionization becomes structured into filaments or striations aligned along the geomagnetic field. Propagation through the structured region results in phase fluctuations if there is relative motion between the propagation path and the structured region. The rms value of the phase fluctuations (variance) is proportional to the square root of the integral of the mean electron density squared along the propagation path in the region and is inversely proportional to the propagation frequency:

$$\sigma_\phi \propto \frac{1}{f}\left[\int \bar{N}_e^2 \, ds\right]^{1/2} . \qquad (4\text{-}5)$$

The phase variations are also dependent on striation parameters (striation size distribution, number of striations per unit area, electron density distribution within the striations). Figure 4-5 shows the phase variance versus time after burst for a megaton, 200 km burst that can be used to estimate the phase variance for megaton bursts detonated between about 150 and 300 km. As for the other integral quantities, the variance is uncertain by about a factor of 3 at intermediate times and by a larger factor at early and late times.

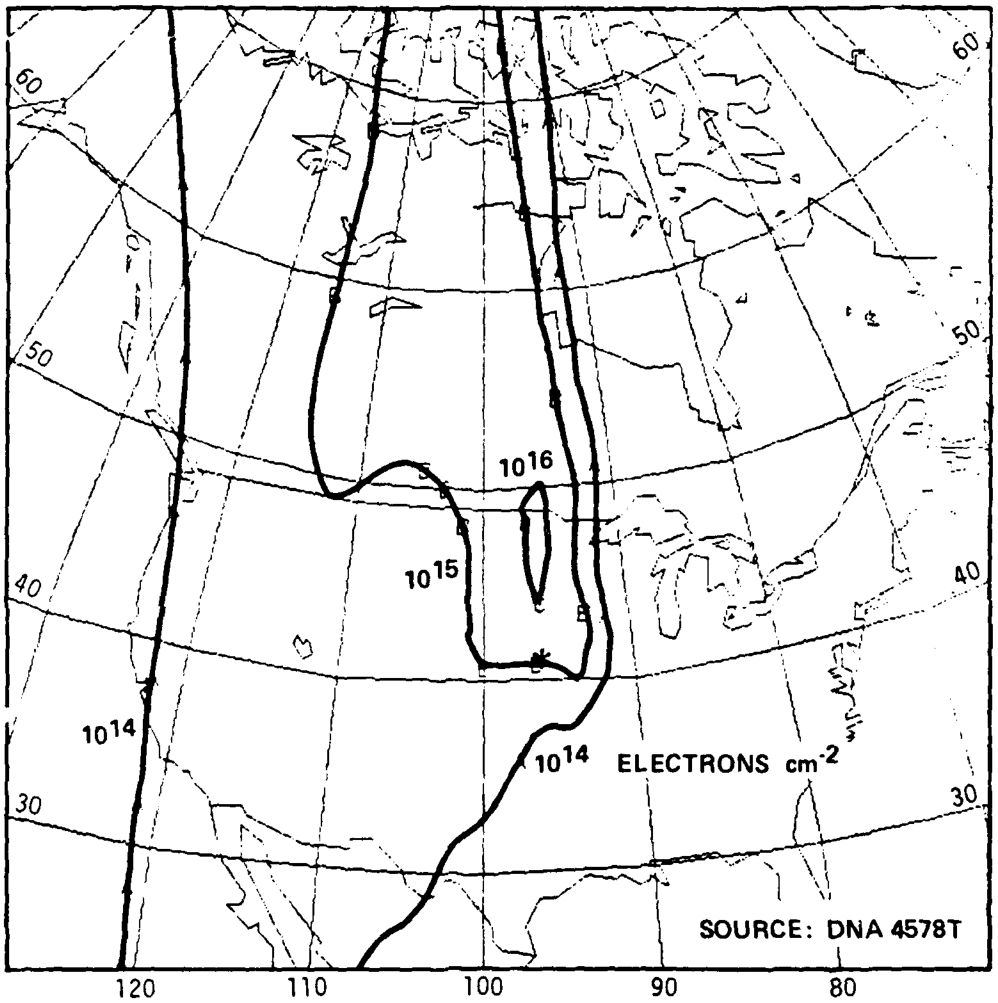


Figure 4-6. Contours of total electron content (1) at 2000 seconds.

After the signal propagates through the striated region, the phase fluctuations produce amplitude fluctuations. In order for the amplitude fluctuations to become fully developed, the signal must propagate a distance

$$z \approx \frac{10^{-5} f}{\text{maximum } (1, \sigma_\phi)} \text{ km} , \tag{4-6}$$

where

f = frequency (Hz) .

For typical synchronous satellite propagation paths through high-altitude fireballs, the amplitude fluctuations are fully developed for propagation in the VHF and lower portion of the UHF bands and can be fully developed well into the SHF band when σ_ϕ is large. The amplitude fluctuations can be estimated from

$$\left(\frac{\overline{\Delta A}}{A}\right)^2 \approx \text{minimum} \left[\left(1, \frac{M(S)}{1 + M(S)}\right)^n \sigma_\phi^{\ 2}\right] , \tag{4-7}$$

where

$$M(S) = \frac{10^5 S(S_T - S)}{S_T f}$$

S_T = distance between transmitter and receiver (km)

S = distance between receiver and striated region (km) ,

and n is between 1 and 2 depending on striation parameters.

Propagation through a striated region also produces angle-of-arrival and time delay fluctuations. Angle-of-arrival fluctuations can cause signal loss if the angular fluctuations are larger than the antenna beamwidth. Time delay fluctuations can be of the order of a microsecond and may affect systems requiring accurate time delay measurements.

In order to determine the effects of amplitude and phase fluctuations on communication and navigation systems, it is necessary to specify the phase and intensity (power) probability density functions (first-order statistics) and autocorrelation functions (second-order statistics). When the amplitude fluctuations are fully developed, the signal intensity probability density can be approximated by a Rician distribution. At closer distances to the striated region non-Rician distributions may be necessary. The phase probability density is usually described as a zero mean Gaussian distribution. Exponential and Gaussian distributions have been used for phase and intensity autocorrelation functions with correlation times approximated from

$$\tau_\phi \approx \frac{1.5}{V_\perp} \text{ s} \tag{4-8}$$

$$\tau_I = \frac{\tau_\phi}{\sigma_\phi} \ s \ , \qquad (4\text{-}9)$$

where τ_ϕ and τ_I are the phase and intensity co-relation times respectively, and $V_\perp$ is the relative velocity (km/s) of the propagation path normal to the striation axis. Typical velocities vary from about 1 kilometer per second at early times to a few tenths of a kilometer per second at late times. In recent theoretical work the signal statistics are generated by simulating propagation through multiple phase screens where the phase power density function at each screen is specified. Also, recent theoretical and experimental work indicate that a power law (f^{-3}) signal power spectrum should be used to characterize the reasonable worst-case signal structure.

In addition to uncertainties in the signal statistics, there is considerable uncertainty in the onset, decay, and spatial dependence of scintillation. The large spatial region that can be affected by high-altitude fireballs is illustrated in Figure 4-7 for the same conditions used for Figure 4-6. The contours are the phase variance for a 7.5 GHz signal.

In order to illustrate critical link and environmental parameters and illustrate the order of magnitude of effects, example results for binary FSK and PSK synchronous satellite to ground links are given below.

Figure 4-8 shows binary FSK average bit error probability versus the bit energy-to-noise density ratio. The curve labeled Slow Rayleigh Fading is for conditions where the amplitude fluctuations are fully developed (generally the case for UHF propagation), the phase variance is greater than about 3 radians, and the amplitude fluctuations occur slowly in comparison to the signal bit period ($T_b << \tau_I$ where τ_I is the signal intensity correlation time; see Equation 4-9). For more rapid fading the fading rate and the normalized FSK tone separation (defined by

$$n = T_b \Delta f \ , \qquad (4\text{-}10)$$

where Δf is the FSK tone separation) are important in determining the bit error rate. Figure 4-8 shows bit error rates for parametric values of T_b/τ_I and a nominal value of n.

Figure 4-9 shows binary phase shift keying (BPSK) bit error probability versus the bit energy-to-noise density ratio for the specified phase lock loop (PLL) parameters. For fast fading the bit error rate is given for parametric values of T_{PLL}/τ_I, where T_{PLL} is the phase lock loop time constant (reciprocal of the phase

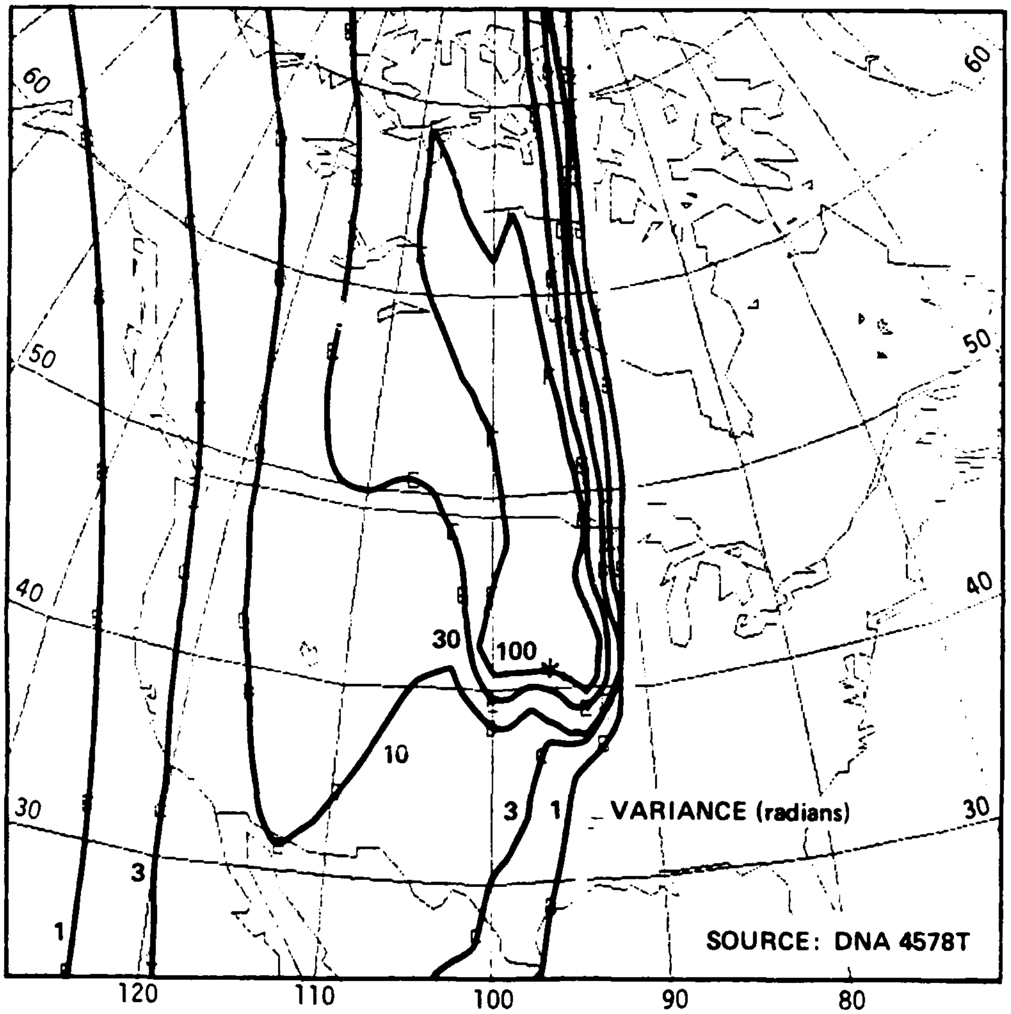


Figure 4-7. Contours of phase standard deviation (σ_ϕ) at 2000 seconds.

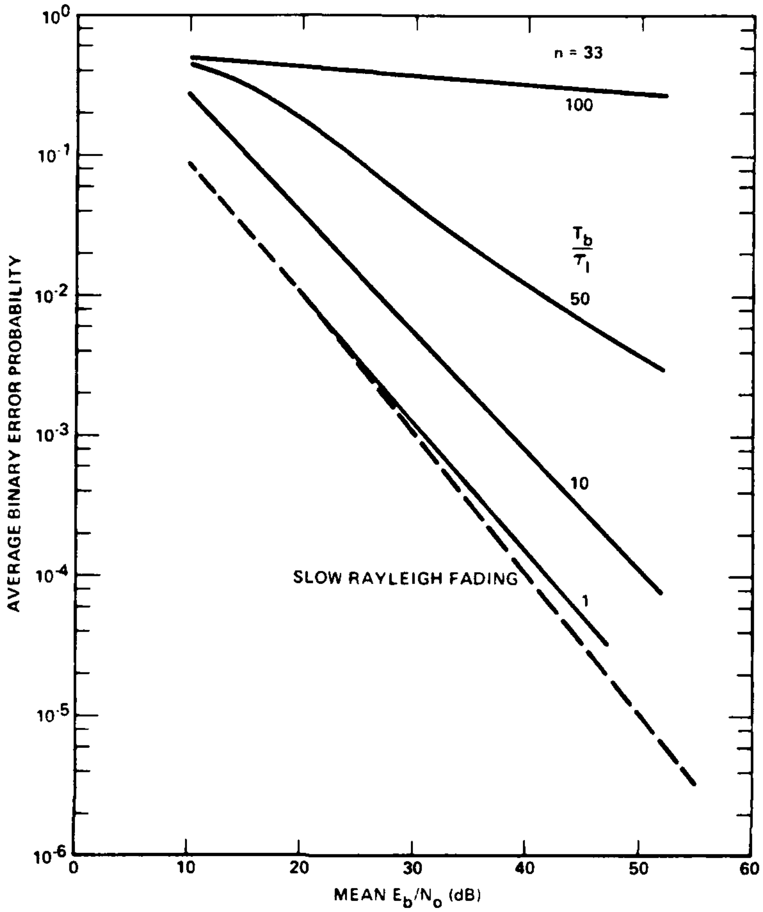


Figure 4-8. FSK average binary error probability versus mean E_b/N_o.

lock loop bandwidth). For small values of T_{PLL}/τ_I, the PLL can track the phase variations and the bit error rate approaches that for amplitude fluctuations only. As the value of T_{PLL}/τ_I increases, the bit error rate for a given value of E_b/N_o increases due to PLL tracking errors. The results shown in Figure 4-9 depend on assumptions concerning the phase and amplitude autocorrelation functions and on other signal processing quantities such as automatic gain control.

The average bit error rates shown in Figures 4-8 and 4-9 can be difficult to interpret in terms of message error probability. Errors are not uniformly distributed in time, tending instead to occur in clumps or bursts with relatively long periods when the bit error rate is much lower than the average.

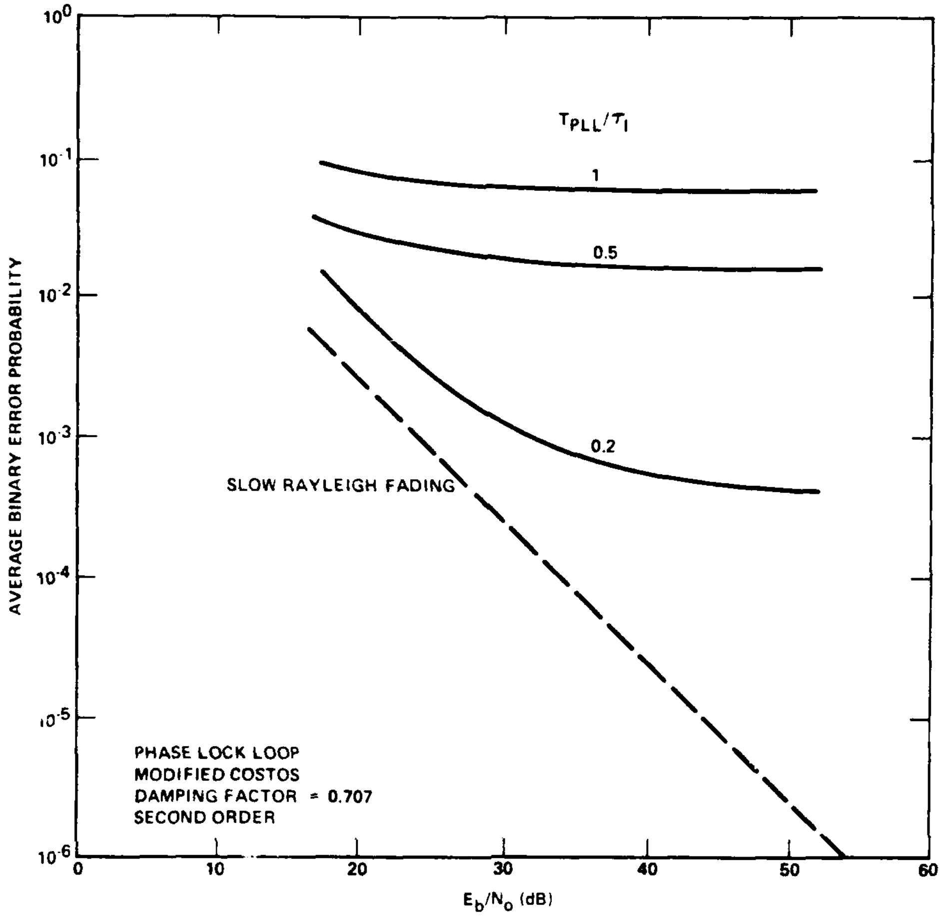


Figure 4-9. PSK average binary error probability versus mean E_b/N_o.

4.3.3 D-Region Absorption

Figure 4-10 shows the one-way vertical absorption due to delayed radiation as a function of the spread debris parameter defined in Section 1.3.7.2. For the data in Figure 4-10 to be applicable, the fission debris must be above about 80 km and the propagation path must traverse the D-region beneath the debris.

Values of the parameter w greater than 10^{-8} MT km^{-2} s^{-1} can be produced over limited regions for a few minutes after burst. For example, the debris horizontal radius for a 4 MT, 80 km burst is about 40 km at 30 seconds after burst. Assuming a 50-percent fission yield, the parameter w is

$$w = \frac{2}{\pi(40)^2\ (30)^{1.2}} \approx 7 \times 10^{-5} \text{ MT km}^{-2}\text{ s}^{-1} . \qquad (4\text{-}11)$$

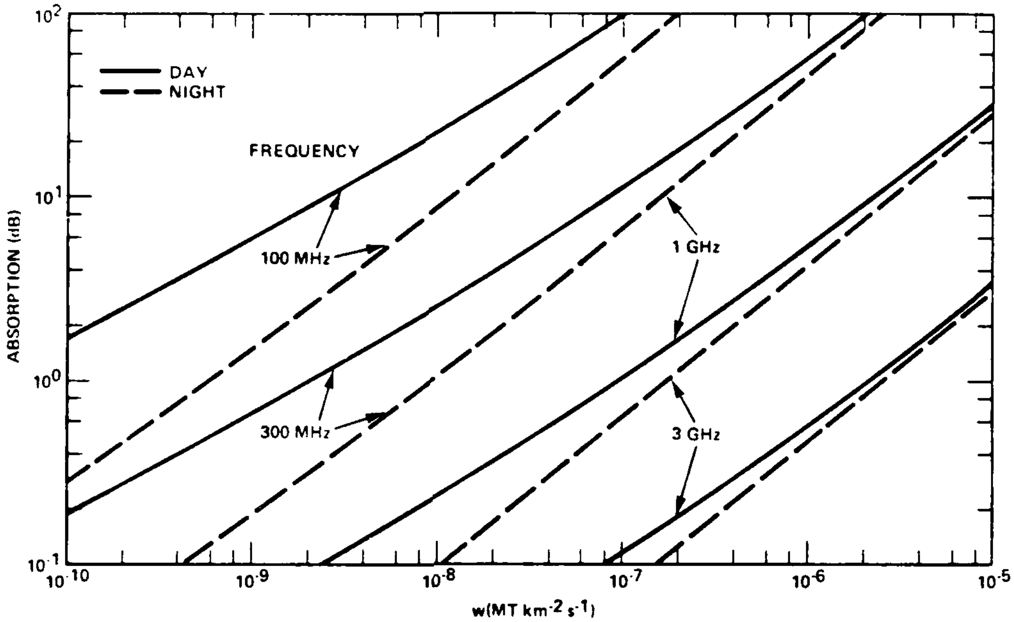


Figure 4-10. One-way vertical absorption due to delayed radiation.

For a similar burst at 200 km the value of w at 60 seconds is about 8×10^{-8} MT km^{-2} s^{-1}.

For large-yield bursts, the absorption in the VHF band and lower UHF band can be several times larger than that shown in Figure 4-10 for a few tens of seconds due to effects of prompt radiation on the neutral species concentrations.

4.4 LINK PERFORMANCE

4.4.1 General

The major parameter determining link performance is the signal-to-noise ratio, which for digital systems is best described by the bit energy-to-noise density ratio defined by

$$\frac{E_p}{N_o} = \frac{P_r}{N_o} T_b \quad , \tag{4-12}$$

where

$\frac{P_r}{N_o}$ = received carrier power-to-noise spectral density (s^{-1})

$= \frac{S}{N_o} B$

$\frac{S}{N_o}$ = signal-to-noise ratio

B = bandwidth (Hz)

T_b = bit period (reciprocal of data rate) (s) .

In a nuclear environment the bit energy-to-noise density ratio is primarily affected by burst-produced absorption and noise. Faraday rotation, refraction, and scattering can reduce signal levels for linear-polarized narrow beam antennas, but are generally unimportant for circular-polarized broadbeam antennas used in communication. Dispersion can reduce signal levels or increase the effective noise by modifying the signal spectrum, but these effects are generally associated with large signal reductions due to absorption.

The signal time delay caused by burst-produced ionizati . can affect systems dependent on accurate timing such as navigation systems.

The basic parameter determining scintillation effects is the phase variance. When the receiver is far enough from the striated region that amplitude fluctuations are fully developed, the random signal power can be completely specified in terms of the phase variance. Otherwise the relative location of transmitter, striated region, and receiver are also required. Other parameters required in determining scintillation effects are the phase and amplitude correlation times and autocorrelation functions (see Section 4.3).

4 ' 2 Communication Links

Performance analyses have been made for line-of-sight links for a variety of strategic and tactical uses (see Bibliography). Some conclusions from these analyses are given below:

4.4.2.1 Subionospheric LOS Links. Subionospheric (below about 50 km) LOS links can be degraded if the propagation path traverses fireball or dust cloud regions. The major degradation effect is absorption and the duration of significant effects is a few minutes after burst. Fireball regions are a few kilometers in radius and rise through their own dimensions in a few tens of seconds. Generally the duration of degradation is determined by the relative motion of the propagation path and fireball region.

For near-surface bursts, dust clouds can be produced within the fireball, within a stem region below the fireball, and in a surface or pedestal region. Dust cloud absorption increases with propagation frequency and may be important in the SHF and EHF bands. SHF and EHF propagation through dust clouds may also experience persistent scintillation effects.

4.4.2.2 Transionospheric LOS Links. Transionospheric LOS links can be degraded if the propagation path is in or close to a fireball region or the D-region is affected by delayed radiation from debris regions.

Debris regions above about 80 km can produce sufficient D-region absorption to affect VHF and lower UHF propagation for up to a few minutes after burst. The size of the region affected can vary from a few tens of kilometers (UHF) to a few hundreds of kilometers (VHF) in radius.

Burst-produced degradation in and above the upper UHF band is essentially limited to the fireball region. For bursts below about 80 km, the dominant effect is absorption and the duration is generally determined by relative motion between the fireball and propagation path. For higher altitude bursts, phase effects due to the mean electron density (time delay, dispersion) and due to fluctuations in electron density (scintillation) can persist long after absorption becomes negligible (from tens of minutes to perhaps a few hours). Also, high-altitude fireballs are large and propagation paths may be in or near the fireball for extended periods.

Signal scintillation is likely to be the most widespread and long lasting propagation effect for high-altitude bursts. The extent of the region producing scintillation can be hundreds to thousands of kilometers, and effects can persist for up to several hours or longer. The spatial and time extent of signal scintillation from natural or nuclear ionization structure decrease with increasing frequency, with all frequencies up to tens of gigahertz being potentially degraded.

4.4.2.3 Scintillation Effects.* Optimum modulator-demodulator design may allow reduction of scintillation degradation due to phase effects so that performance approaches that of slow Rayleigh fading. Coherent phase-shift-keyed links in particular require careful selection of tracking-loop bandwidths to avoid serious degradation due to rapid phase scintillations. Low data rate systems are severely degraded when the signal scintillation rate exceeds a fundamental rate characteristic of the demodulator. For frequency-shift-keyed (FSK) links, the modulation rate is usually the critical factor. For PSK links the minimum of the phase-tracking-loop bandwidth or the modulation rate is the limiting factor. Coherent PSK demodulation should be avoided in slow data rate systems. Either noncoherent FSK or differentially coherent PSK demodulation should be used.

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* This summary of scintillation effects was largely taken from a summary by the Mitigation Techniques Working Group formed during the DNA/LASL High Altitude Nuclear Weapons Effects Summer Study held in August 1978, at Los Alamos, New Mexico.

For all links, amplitude fading produces significant reduction in performance even when fade-rate problems are mitigated. Additional performance gains from amplitude mitigation are likely to require some forms of coding, interleaving, message repetition, and increased signal power.

Frequency diversity from frequency hopping can improve the performance of coded links in frequency-selective scintillation conditions, but optimal demodulator design and time-diversity techniques should also be used. Use of frequency hopping as an anti-jam (AJ) technique is generally compatible with anti-scintillation (AS) mitigation.

Frequency diversity from pseudo-noise (PN) spread spectrum can degrade link performance in frequency-selective scintillation conditions. Use of PN spread spectrum for AJ is generally contradictory to AS protection, and PN systems require careful evaluation of AJ/AS performance.

Spatial diversity from appropriately spaced antennas and interconnected receiving systems can offer significant protection against scintillation fading. The minimum antenna separation is about 1 km at UHF, decreasing to around 100 m at EHF.

4.4.2.4 Major Uncertainties. The major uncertainties in predicting transionospheric LOS link performance are due to uncertainties in predicting fireball geometry and properties for bursts detonated above about 80 km. Predictions of the late-time (tens of minutes to hours) fireball mean electron density and temperature distributions are based on relatively few detailed theoretical calculations. Predictions of striation parameters (onset time, size distribution, decay) are also based on limited experimental and theoretical data. Scintillation predictions at high SHF and EHF frequencies are more sensitive to uncertainties in nuclear phenomenology than predictions at lower frequencies.

Predictions of subionospheric LOS links that are affected by dust cloud regions are uncertain due to uncertainties in modeling the spatial distribution of dust clouds and imcomplete modeling of scintillation effects.

4.4.3 GPS

Studies of GPS location measurement accuracy when one of the four satellite signals (see Section 1.2.4.3 for description of GPS) propagates through a nuclear environment have been made (see Bibliography). Conclusions from these studies are:

1. Signal time delays and time rate of change in signal time delays due to the mean electron density along the path can cause severe position errors even when the dual frequency correction is used.

2. Amplitude and phase scintillations can destroy velocity information.
3. Jam-resistant receiver configurations with very narrow carrier loop bandwidths are particularly susceptible to degradation.
4. Recommended nuclear effects mitigation includes: (a) avoidance, and (b) receiver performance modifications.

Avoidance of nuclear-affected links is possible since from six to eleven satellites will be visible at any given location, and signals from only four are required. Procedures for determining when a satellite signal has been degraded by nuclear effects have been studied.

Suggested receiver performance modifications include use of limiting and changing the order and bandwidth of phase tracking loops.

SECTION 5

TROPOSCATTER PROPAGATION

5.1 GENERAL

Tropospheric forward-scatter propagation is used for beyond line-of-sight communications where the nature of the terrain makes other means of highly reliable communication difficult. Troposcatter links operate in the UHF and SHF bands over distances of 80 to about 600 km. Single-link distances of several hundred kilometers are typical, particularly for tactical use. Tandom operation of two or more links can be used for distances up to several thousand kilometers.

5.2 PROPAGATION IN THE NATURAL ENVIRONMENT

Figure 5-1 illustrates the geometry of a troposcatter link. Propagation from transmitter to receiver is via scatter in the common volume in the troposphere. Scattering efficiency decreases with increasing altitude of the common volume, and elevation angles are normally kept as low as intervening terrain permits. For short links the common volume is between about 1 and 3 km altitude, while for longer links it is between about 5 and 15 km. The scattering loss in the common volume results in a received signal that is between 50 and 90 dB below the free-space signal, depending on frequency and common volume altitude and size.

Propagation in the natural atmosphere is characterized by 20 to 40 dB signal fades due to multipath. Multipath interference results from signals being received from different parts of the scattering volume. Multipath propagation also introduces adjacent-channel interference, which appears as background noise and places an upper limit on the bandwidth that can be successfully transmitted. For high-quality systems, physically large antennas are employed to reduce the beamwidth and thus the size of the scattering volume. Also, space diversity is used by having two or more spaced receiving antennas.

Received noise is determined by receiver noise, adjacent-channel interference, or by interference from other signals.

5.3 PROPAGATION IN A NUCLEAR ENVIRONMENT

Since the troposcatter propagation path is generally below about 10 km, only low-altitude-burst fireball and dust regions can affect the normal signal.

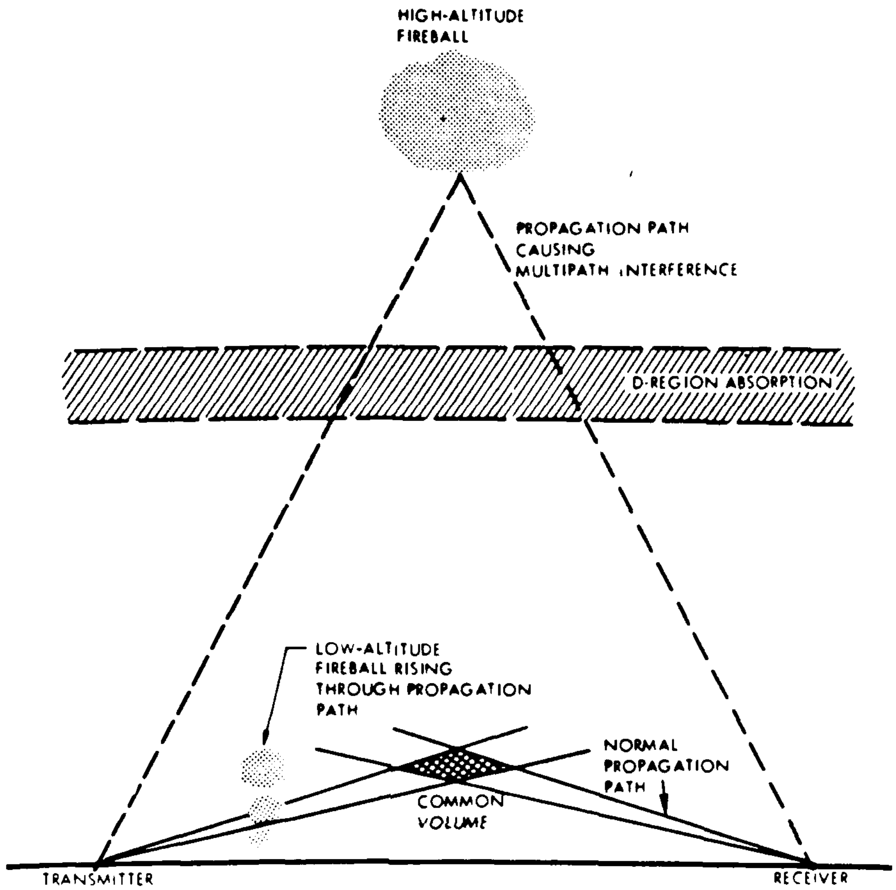

Figure 5-1. Illustration of troposcatter geometry.

Multipath signals and thermal noise can result from fireball regions outside of the normal propagation path, particularly from high-altitude fireball regions (see Figure 5-1).

A low-altitude burst placed so that the fireball will rise through the normal propagation path will attenuate the signal by fireball absorption. Figure 4-1 shows an example of fireball absorption for a 1 MT surface burst. The attenuation can last for a few minutes; however, the duration is generally determined by fireball motion carrying the fireball out of the antenna beam.

Because the normal signal is 50 to 90 dB below a free-space signal, scattering from the fireball can produce an interfering signal even when the fireball is in the antenna side lobes. Generally the signal scattered from low- and intermediate-altitude fireballs is too small to interfere with the normal signal.

Signals scattered from high-altitude fireballs can cause multipath interference for a few minutes after burst. D-region absorption will reduce the multipath signal and may delay the onset of interference.

Fireball thermal noise can increase received noise depending on frequency, antenna pattern, and fireball properties. Generally, fireball thermal noise is negligible in comparison to normal receiver input noise; however, use of very-low-noise receiving systems would result in significant degradation.

Increased noise levels may result from interference from other sources (troposcatter links, line-of-sight links, radar) propagated to the receiver via fireball scattering. For low-altitude fireball regions placed so that they are in the main beam of the interfering signal antenna pattern and in the main beam of the troposcatter receiver antenna pattern, significant scattering from dust and from water vapor entrained into the fireball may persist for tens of minutes. The duration will be limited by motion of the scattering region, and for less favorable burst locations interference will be limited to a few tens of seconds.

5.4 LINK PERFORMANCE

The major sources of potential link degradation are absorption, thermal noise, and adjacent-channel interference due to multipath. Link vulnerability studies presented in the DNA Communications System Handbook (summarized in Table 5-1) and recent studies (see Bibliography) indicate that link degradation is likely to be short lived (tens of seconds) and only result from bursts detonated in a limited geometrical region.

Scattering and refraction from water vapor and dust may prolong degradation, but preliminary studies indicate that the degradation could only occur for special burst and link geometries and is not likely.

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SECTION 6

METEOR BURST AND IONOSCATTER PROPAGATION

6.1 GENERAL

Ionospheric forward-scatter propagation can be used to extend VHF propagation beyond line-of-sight distances. Frequencies between 30 and 150 MHz are used for propagation distances up to about 2000 km. While most of the past applications have been displaced by satellite links, there is continuing interest in beyond line-of-sight VHF propagation for use in nuclear-disturbed environments.

6.2 PROPAGATION IN THE NATURAL ENVIRONMENT

Two basic methods have been used to establish a useful ionospheric scatter propagation path. The ionoscatter link method uses the continuously present but weak and variable signals scattered from the ionosphere for continuous low-data-rate transmissions. The meteor burst link method stores the traffic and subsequently transmits these data at high data rates when the signal can be scattered or reflected from a meteor trail.

Operation of an ionoscatter link depends on scattering of energy from the upper D- and lower E-regions; maximum scatter is believed to occur between 70 and 90 km. The detailed scattering mechanisms are uncertain, but scattering appears to be due to turbulent mixing producing electron density inhomogeneities.

Ionoscatter systems typically operate at frequencies significantly above the maximum usable E- and F-layer reflection frequencies (MUF's) to minimize multipath reflections and HF interference. Usually two-frequency operation is preferred; the 35 MHz range is used for low transmission loss, and the 60 MHz range is used to avoid multipath interference at times of high solar activity. Operation in the higher frequency range requires greater transmitter power and possibly reduced channel capacity as compared to operation in the lower frequency range.

Scattering losses vary from 50 to 100 dB relative to free space depending on season, time of day, geographic location, antenna pattern, path length, and frequency. Substantial changes in the scattered power can occur from one hour to the next. Multipath interference due to signals scattered from different parts of the scattering region result in rapid amplitude fluctuations and limit the maximum data rate that can be used. Multipath interference also occurs due to scattering from meteor trails, E- and F-region ionization, and auroral ionization. Generally space diversity is used to reduce the effects of amplitude fading. The dominant noise source is cosmic noise, which results in an equivalent antenna temperature of several thousand degrees (frequency dependent).

Because of the weak signal strength, rapid signal fading, and frequency-selective fading, ionoscatter links are most suitable for low-data-rate teleprinter operation.

Meteor-burst links depend on propagation via meteor trails (ionized regions) produced between 80 and 120 km by meteors impinging on the atmosphere. Typically, several hundred meteor trails per hour are positioned and aligned properly to allow specular reflection of VHF signals. Many more underdense trails occur that produce weaker signals via scattering.

In operation a master station continuously transmits a probing signal. When a slave station receives this signal, it immediately notifies the master station using the same meteor trail. Each station can then send and receive traffic alternately or simultaneously at relatively high data rates.

Meteor-burst propagation provides a unique anti-jam protection when the jammer is not within line-of-sight of a station. This is due to the low probability that a meteor trail can support propagation from the jammer to the station and from the transmitter to the station.

6.3 PROPAGATION IN A NUCLEAR ENVIRONMENT

Ionoscatter and meteor-burst links are susceptible to D-region absorption produced by prompt and delayed radiation. Because of the relatively low frequencies used, absorption can be appreciable. However, since absorption scales inversely as frequency squared, the magnitude of absorption is much less than for propagation in the HF band. Changes in the D-region electron density will also affect the amount of energy scattered from electron density inhomogeneities. Whether signal enhancement or degradation will occur depends on the link common volume, the location of the normal and disturbed scattering regions, and the amount of absorption.

Figure 6-1 shows the relevent geometry for a 1500 km ionoscatter link and the D-region ionization produced by a 30 km burst detonated 250 km from the center of the link. The bottom of the common volume is at about 45 km, and the region of most efficient scattering for undisturbed conditions is between 75 and 90 km. The burst-produced absorption region reduces the amount of energy propagated between Site 1 and most of the normal scattering region. If the burst produced more widespread ionization or was located closer to the center of the path, scattering from

the common volume below the normal scatter region could be important in maintaining link connectivity when scattering from the normal scatter region was attenuated. For longer links the bottom of the common volume will be above the absorption region and energy scattered from the bottom of the common volume will also be attenuated. Meteor-burst links generally will not have sufficient sensitivity to use scattering from D-region ionization inhomogeneities and would not recover until signals could be received from the normal scattering region (90 to 120 km).

Figure 6-2 shows the one-way vertical absorption due to delayed radiation as a function of the spread debris parameter defined in Section 1.3.7.2. For the data in Figure 6-2 to be applicable, the fission debris must be above about 80 km. The absorption region occurs between about 60 and 80 km altitude beneath the debris. For other conditions (lower debris altitudes, locations beyond the debris edge), absorption is due to gamma rays and is less than shown.

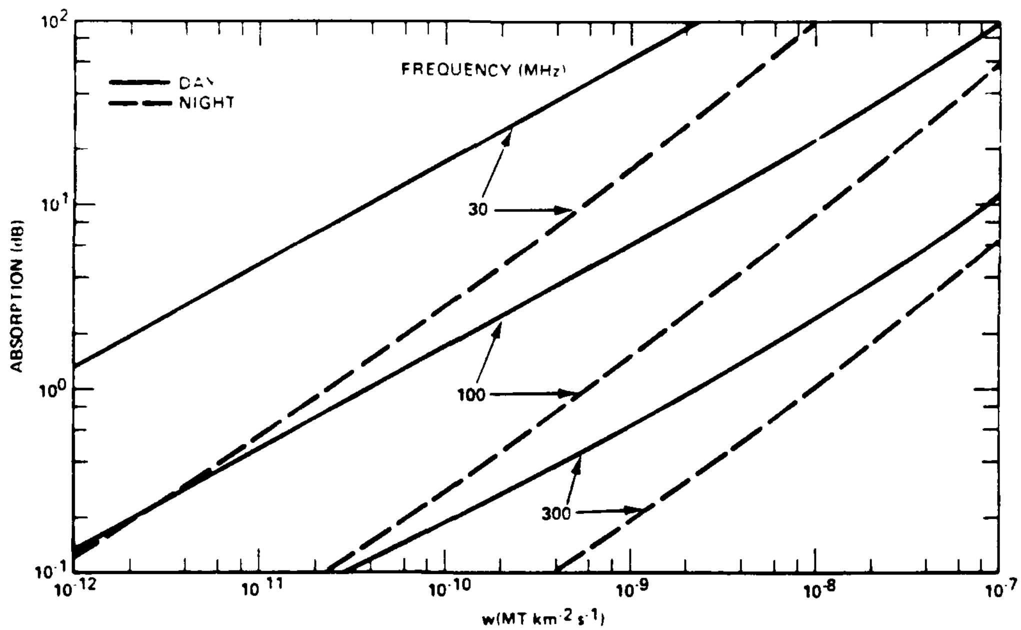

Figure 6-2 One-way vertical absorption due to delayed radiation.

For typical ionoscatter and meteor-burst links, the oblique one-way path absorption is about 5 times the vertical path absorption (angle of incidence in the D-region of about 80 degrees). Thus, if the absorption region is large enough to affect propagation from both sites to the common volume, the total absorption will be about 10 times the one-way vertical absorption shown in Figure 6-2. For a 20 dB margin, recovery of a 100 MHz link would not occur until the spread debris parameter w was less than about 10^{-10} MT km^{-2} s^{-1} for daytime conditions. As discussed in Section 1.3.7.2, this value of w can be produced for several hours over relatively large regions.

Fireball regions in and below the D-region can attenuate and scatter signals. Generally the size of the fireball is small in comparison to the normal scattering region, and the fireball ionization decays relatively quickly. Fireballs in the E- and F-regions can be large, and scattering of energy in the VHF band may persist for tens of minutes or longer. Shock waves and acoustic gravity waves can also affect the normal E- and F-regions producing increased scattering.

Quantitative results for high-altitude fireball scatter and E- and F-region scattering are incomplete, particularly for high latitudes of interest.

Thermal noise from the burst-produced fireball has negligible effect because of the high cosmic noise levels.

6.4 LINK PERFORMANCE

The major source of degradation to ionoscatter and meteor-burst links is due to D-region absorption produced by delayed radiation. Meteor-burst links and ionoscatter links that are longer than about 1500 km can be blacked out for periods of an hour or so for moderate to severe nuclear weapon environments. Ionoscatter links that are less than 1500 km may be able to operate in severe environments because of signal energy scattered from the bottom of the common volume.

Table 6-1 shows outage times calculated for three ionoscatter links for a variety of weapon environments. The early recovery of the shorter links is due to scattering from burst-produced ionization within the common volume. The long duration outage for the 2000 km link occurs because the bottom of the common volume is above the burst-produced absorption region. Revisions to atmospheric chemistry models since Table 6-1 was prepared would reduce the predicted maximum duration of outage to a few hours.

Multipath signals from high-altitude fireballs and ionized portions of the E- and F-regions affected by prompt energy deposition and traveling disturbances may require use of reduced bandwidths.

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The following documents describe nuclear weapons effects on communication and navigation systems. They are listed under the categories listed below. In each category handbooks are listed first followed by reports. Both the handbooks and reports are listed in reverse chronological order (most recent document first).

GENERAL EFFECTS OF NUCLEAR WEAPONS AND SUMMARY DESCRIPTIONS OF WEAPON EFFECTS ON COMMUNICATION SYSTEMS

HANDBOOKS

U.S. Departments of Defense and Energy, *The Effects of Nuclear Weapons,* Third Edition, S. Glasstone and P.J. Dolan (ed), U.S. Government Printing Office, 1977.

This book presents an unclassified comprehensive summary of information concerning nuclear weapon effects. In addition to chapters on air blast, ground and water shock, thermal and nuclear radiations, and their effects on man and materials, there are chapters on radio and radar effects.

DNA 3499H (AD A010 228), *Aids for the Study of Electromagnetic Blackout,* W.S. Knapp and K. Schwartz, GE74TMP-33, General Electric—TEMPO, February 1975.

This unclassified report is a compendium of selected graphs, charts, equations, and relations useful in the analysis of electromagnetic blackout caused by nuclear explosions. It is assumed that the user is familiar with material presented in DNA 3380H.

DNA 3380H-1 (AD 532 188), *Electromagnetic Blackout Handbook Volume 1 - Introduction to Nuclear Weapon Effects, Weapon Outputs, and Phenomenology of Heated Regions (U)*, W.S. Knapp, et al, GE74TMP-3, General Electric—TEMPO, September 1974

DNA 3380H-2 (AD C000 208), *Electromagnetic Blackout Handbook Volume 2 - Atmospheric Ionization and Electromagnetic Propagation Effects* W.S. Knapp, et al, GE74TMP-3, General Electric—TEMPO, September 1974

DNA 3380H-3 (AD C000 218), *Electromagnetic Blackout Handbook Volume 3 - Appendixes* , W.S. Knapp, et al, General Electric—TEMPO, September 1974

The *Electromagentic Blackout Handbook* provides an introduction to nuclear weapon effects on electromagnetic propagation (excluding EMP and TREE effects) and detailed descriptions of specific weapon and atmospheric phenomena of interest. Introductory material is similar to that presented in *The Effects of Nuclear Weapons,* DNA EM1, and AFSCM 500-9. Quantitative scaling relations and detailed descriptions of weapon phenomenology and atmospheric effects related to electromagnetic propagation are based on more recent studies and in general are more comprehensive than the other documents.

DNA EM1 (AD 526 125, AD 526 126), *Capabilities of Nuclear Weapons* P.O. Dolan (ed). Parts 1 and 2, Defense Nuclear Agency, July 1972

This two-volume document presents a classified comprehensive summary of information concerning nuclear weapon effects and provides the source material and references used for preparation of operational and employment manuals by the Military Services.

REPORTS

CCTC TP 20-77, *Fiscal Year 1979-1988 MEECN Master Plan*, Defense Communication Agency, February 1977

The FY 1979-1988 MEECN Master Plan (MMP) updates the status of the MEECN in light of OSD/JCS decisions and actions since publication of the preceding FY 1977-1986 MMP. It reports on the updated "Concept of Operations for the MEECN" and on efforts of the CINCs, Services, and other DOD Activities to improve network performance. It also presents an assessment of the performance of the current and programmed MEECN in the post-attack period when the DIA "best-estimate" threat is applied. Moreover, the performance of the Advanced MEECN is assessed primarily for the post-attack period, complemented by a limited number of initial trans-attack analysis results. The contributions of the soft ELF (SEAFARER) system, various SIOP communication systems, and other candidate systems are determined.

DNA 4364F (AD C013 886), *Parametric Sensitivity Analysis of Nuclear Phenomenology*, M.H. McGill, Systems Control, Inc., January 1977

An analysis of the effects of uncertainties in nuclear phenomenology models on MEECN performance.

DNA 3778 (AD 024 956), *An Overview Discussion of Propagation Effects of Nuclear Environments on VLF-LF Communication Systems*, C. Crain, The RAND Corporation, August 1975.

An overview of how nuclear environments can degrade normal communications capability and the consequences of remaining uncertainties in predicting degradation under worst-case conditions.

HD2-CR-75-016-1 (AD C002 803), *Analysis of Typical Theater Army Communication Links in a Nuclear Environment* J.D. Illgen, GE75TMP-17, General Electric—TEMPO, July 1975

The effects of rudimentary nuclear scenarios on representative Theater Army Communication Links are determined. Link parameters are defined using various communication concepts defined by INTACS. Nuclear burst parameters are chosen to provide illustrative time duration and magnitude of effects. Only propagation effects due to atmospheric and ionospheric disturbances are considered. The data are intended to identify potential problem areas and provide guidance for performing more detailed analyses. Recommendations for future analysis are provided.

DNA 3301T (AD 529 694), *An Overview of HF Communications in a Nuclear Environment*, E.J. Bauman, G.H. Smith, D.L. Neilson, W.E. Jaye, SRI Project 2511, Stanford Research Institute, March 1974

A brief review and comment on the utility of HF propagation in a nuclear environment. Defines regions where predictions can be made with confidence.

EFFECTS OF NUCLEAR WEAPONS ON ELF,
VLF, AND LF COMMUNICATION SYSTEMS

HANDBOOKS

DASA 1954-1 (AD 389 214L), *Nuclear Effects on VLF and LF Communication Systems Selected Examples,* Defense Atomic Support Agency, June 1968

DASA 1954-2 (AD 394 550L), *Nuclear Effects on VLF and LF Communication Systems General Prediction Techniques,* Defense Atomic Support Agency, September 1968

This handbook is published in two parts that describe the effects of nuclear bursts on the propagation of very low frequency (VLF) and low frequency (LF) communication systems.

The examples presented in DASA 1954-1 illustrate the approximate duration and extent over which typical systems may experience difficulty. In addition to specific results, a brief tutorial description of the effects of nuclear bursts on radio wave propagation and VLF and LF propagation in natural environments is given.

DASA 1954-2 presents techniques for modeling a relatively wide range of nuclear situations and for predicting how these situations would degrade LF and VLF communication system performance. DASA 1954-1 and DASA 1954-2 provide a basic understanding of nuclear phenomenology and its interrelations with LF and VLF propagation.

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DNA 4440F (AD C015 834), *Dependence of ELF/VLF System Performance on Atmospheric Parameters* E.C. Field, PSR-713, Pacific-Sierra Research Corp., December 1977

An analysis of the effects of uncertainties in effective reaction rate coefficients and ion-neutral collision frequency on ELF/VLF propagation.

AFWL-TR-76-273 (AD C009 770L), *616A Performance in a Nuclear Environment* T.M. Hardbeck and J.M. Kamm, Air Force Weapons Laboratory (DYC), April 1977

This report considers propagation of a highly formatted message from the Strategic Air Command (SAC) transmitter at Silver Creek, Nebraska. Signal-to-noise ratios are calculated for the full wave in a ambient environment and the environment created by a single high-altitude nuclear detonation and for the ground wave only. From these values, message error probabilities and the probability of receiving a complete message which meets stringent acceptability criteria are calculated.

AFWL-TR-76-72 (AD C008 118L), *616A Communication Systems Program—Comparison of Blackout Analysis for Airborne VLF and LF Transmissions* D.G. Morfitt, Naval Electronics Laboratory Center, September 1976

This report is the third of a series which presents propagation analyses of the airborne 487L and 616A systems in both normal and nuclear-disturbed environments (see AFWL-TR-73-185 and AFWL-TR-277). This report examines the propagation of signals from the SACABNCP (SAC Airborne Command Post) and NEACP (National Emergency Airborne Command Post) through a nuclear-disturbed environment as created by the RISOP (Red Integrated Strategic Operations Plan) 72 Sierra weapon laydown. Signal-to-noise ratios and standard deviations are determined and related to the character error rate. Noise levels and their corresponding standard deviations are also given so that CER probabilities can be calculated for any mode.

NRL 8017 (AD B013 384L), *Very Low Frequency (VLF) Propagation Predictions for Disturbed Conditions*, F.J. Kelley, et al, Naval Research Laboratory, July 1976.

A comparison of theoretical VLF attenuation rate predictions for a nuclear-disturbed ionosphere shows that the Naval Electronics Laboratory Center (NELC) waveguide program and the GE—TEMPO WEDCOM program agree very well in the calculation of the first-order transverse magnetic (TM) mode attenuation rates. The agreement for the second-order TM-mode attenuation rates is not as close, but the differences are not very significant for practical predictions.

Between 10 and 25 kHz, for a 4-Mm path length, the cumulative attenuation of the transverse electric (TE) mode signal is greater than that of the TM-mode signal by at least 45 dB under the disturbed condition assumed in the present calculation. In addition, the horizontally polarized TE mode waves are more attenuated than the TM-mode wave under the normal condition.

DNA 3778 (AD 024 956), *An Overview Discussion of Propagation Effects of Nuclear Environments on VLF-LF Communication Systems*, C. Crain, The RAND Corporation, August 1975.

An overview of how nuclear environments can degrade normal communications capability and the consequences of remaining uncertainties in predicting degradation under worst-case conditions.

AFWL-TR-74-277 (AD C004 076L), *616A Blackout Analysis for Airborne Transmissions*, D.G. Morfitt, Naval Electronics Laboratory Center, November 1975

The 616A Survivable Low Frequency Communications System is designed to transmit essential messages from national command authorities. This study examines the propagation of signals from the airborne command posts SACABNCP (SAC Airborne Command Post) and NEACP (National Emergency Airborne Command Post) through a nuclear-disturbed environment as created by the RISOP (Red Integrated Strategic Operations Plan) 72 Sierra weapon laydown. Signal strengths are calculated at SACABNCP for 44.0-kHz transmissions from NEACP and at NEACP for 39.2-kHz transmissions from SACABNCP. Calculations are also made for transmissions from SACABNCP to the Malmstrom Air Force Base Minuteman site, to Hickam Air Force Base in Hawaii, and to the Green Pine sites at Point Barrow, Alaska, and Thule, Greenland. Signal-to-noise ratios are determined and related to the character error rate (CER). Probabilities of achieving various values of CER are computed.

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E.C. Field and M.A. Dore, PSR 505, Pacific-Sierra Research Corporation, July 1975).

This report presents calculated phase and amplitude time histories for generic nuclear environments and discusses the results in terms of communication system performance.

NESC PME-117 (AD C002 772), *Propagation of ELF Waves (45 and 75 Hz) in a Nuclear Environment* W.F. Moler and L.R. Shockey, NELC TR 1953, Naval Electronics Laboratory Center, June 1975

This report, prepared for Naval Electronics System Command, gives bounds on expected path losses and phase changes in nuclear environments.

AFWL-TR-73-185 (AD 528 186L), *487L Blackout Analysis for Airborne Transmissions* D.G. Morfitt, et al, Naval Electronics Laboratory Center, December 1973

The 487L Survivable Low Frequency Communications System is designed to transmit essential messages from national command authorities, the commanders-in-chief of various strategic forces, or their alternates. This report examines the propagation of signals from the airborne command posts Looking Glass (SAC Airborne Command Post) and NEACP (National Emergency Airborne Command Post) through a nuclear-disturbed environment as created by the RISOP (Red Integrated Strategic Operations Plan) 72 Sierra weapon laydown.

Signal strengths are calculated at Looking Glass for 44.0-kHz transmissions from NEACP and at NEACP for 39.2-kHz transmissions from Looking Glass. Calculations are also made for transmissions from Looking Glass to the Malmstrom Air Force Base Minuteman site and to the Green Pine sites at Point Barrow, Alaska, and Thule, Greenland. Signal-to-noise ratios are determined and related to the character error rate (CER). Probabilities of achieving various values of CER are computed.

EFFECTS OF NUCLEAR WEAPONS ON HF COMMUNICATION SYSTEMS

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DASA 1955-1 (AD 389 214L), *Nuclear Effects on HF Communication Systems, Selected Examples,* Defense Atomic Support Agency, October 1967

DASA 1955-2 (AD 393 462L), *Nuclear Effects on HF Communication Systems General Prediction Techniques,* Defense Atomic Support Agency, April 1968

This handbook is published in two parts that describe propagation effects of nuclear bursts on high-frequency communication systems.

The examples presented in DASA 1955-1 illustrate the approximate duration and extent over which typical systems may experience difficulty. In addition to specific results, a brief tutorial description of the effects of nuclear bursts on radio wave propagation and HF propagation in natural environments is given.

DASA 1955-2 presents techniques for modeling a relatively wide range of nuclear situations and for predicting how these situations would degrade HF communication system performance. DASA 1955-1 and DASA 1955-2 provide a basic understanding of nuclear phenomenology and its interrelation with HF propagation.

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This study evaluates the sensitivity of HF communication system performance to variations in atmospheric parameters in order to establish requirements for new or more accurate atmospheric measurements.

DNA 435T-1 (AD C015 994), *Integrated Nuclear Communications Assessment (INCA); Cemetery Net Performance in an Air Defense Nuclear Environment* S.L. Gutsche, Mission Research Corp., December 1977

This report describes the second phase of an MRC effort in support of the Integrated Nuclear Communications Assessment (INCA) Program. Information is presented regarding an assessment of the performance of certain links of the Cemetery Net Communication system in a nuclear environment produced by air defense bursts.

CCTC TP-11-76 (AD C006 494L), *Advanced MEECN High Frequency Communication System Concept Formulation* G.B. Westmore and J.M. Kelso, IIT Avionics Division, Electro-Physics Laboratories, March 1976).

Describes MEECN requirements, HF propagation in undisturbed and disturbed environments, and a description of an advanced high-frequency system.

DNA 3905F (AD C009 327), *INCA PHASE I: Study of the Effect of a Tactical Nuclear Environment on the Performance of EM Systems* . J.G. Depp. et al, Stanford Research Institute, December 1975

High-frequency propagation under tactical nuclear conditions is described. The weapon effects on skywave propagation, both long and short range, and on groundwave propagation are discussed. Particular emphasis is placed on CEMETERY NET propagation. Effects are also described for Nike-Hercules antiaircraft nuclear detonations at maximum altitude and maximum yield and for high-altitude detonations above 50 km.

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A semigraphical, semianalytic procedure is described and used to define an anticommunications link attack. Nuclear burst yield, altitude, and time are determined to maximize the effects on specified LF and HF propagation links. An example attack generated by the procedure is given, and the results achieved by the attack are computed and discussed.

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A study is made of the absorption of HF communications signals in the nuclear environment caused by a mass attack on the United States. The effects of meteorological conditions, particularly wind profiles, on the outage times are observed. Average communications link reconstitution times, sensitivity of the result to time of day of the attack, effects of debris stabilization altitudes, and seasonal dependences are examined for 12 specific links of interest.

DNA 3798T (AD C006 002), *Adaptable HF Communication Systems for Use in a Nuclear Environment* T.W. Washburn and G.H. Smith, SRI Project 2511, Stanford Research Institute, September 1975

This report describes a number of techniques for improving the performance of HF communication systems in a nuclear environment.

NOLTR74-36 (AD 531 028L), *Shipboard High-Frequency Radio Communication Blackout Resulting from High-Altitude Nuclear Bursts* L.R. Herschel and L.F. Lebelo, Naval Ordnance Laboratory, June 1974

This report considers the phenomenology and effects of a nuclear multiburst situation on ship-to-ship HF communications as determined from NUCOM code results. The multiburst situation discussed arises from the defensive use of nuclear weapons against ballistic missile reentry where several multimegaton weapons are detonated in a short time. The resulting HF communication degradation is severe with possible "outages" (depending upon propagation path, frequency, and distance from burst) of long duration. Also discussed in this report are outages and processing delays under "normal" conditions of ionospheric propagation.

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A brief review and comment on the utility of HF propagation in a nuclear environment. Defines regions where predictions can be made with confidence.

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A general study of HF performance in single-burst nuclear environments. Propagation paths from 950 to 6000 km and frequencies between 2 and 30 MHz are evaluated for times after burst from 5 minutes to 12 hours.

EFFECTS OF NUCLEAR WEAPONS ON LINE-OF-SIGHT SYSTEMS

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This two-volume document updates and replaces much of the material in DASA 1956-1 relating to satellite systems.

DASA 1956-1 (AD 390 254L), *Nuclear Effects on Satellite and Scatter Communication Systems Selected Examples*. Defense Atomic Support Agency, October 1967).

DASA 1956-2 (AD 394 007L, AD 395 197L), *Nuclear Effects on Satellite and Scatter Communication Systems , Volume 1: General Prediction Techniques for Satellite Systems*, July 1968; *Volume 2: General Prediction Techniques for Scatter Systems*, October 1968, Defense Atomic Support Agency (

This handbook contains two parts. Part 1 (DASA 1956-1) describes the propagation effects of selected nuclear bursts on satellite and scatter communication systems. The examples illustrate the approximate duration and extent over which typical systems may experience difficulty. In addition to specific results, a brief tutorial descriptions of the effects of nuclear bursts on radio wave propagation in natural environments is given.

Part 2 (DASA 1956-2), consisting of two volumes, describes the effects of nuclear bursts on the propagation of satellite communication systems (Volume 1) and troposcatter and ionoscatter communication systems (Volume 2). Techniques to model a relatively wide range of nuclear situations and to predict how these situations would degrade the communication systems performance are presented. These volumes provide a basic understanding of nuclear phenomenology and its interrelation with troposcatter propagation and propagation to satellites.

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DNA 4736P-1, *Satellite C³ Nuclear Mitigation Techniques Volume I - Summary from DNA/LASL High Altitude Nuclear Weapons Effects Summer Study (U)*, L.A. Wittwer and R.L. Bogusch, Defense Nuclear Agency, November 1978

The Defense Nuclear Agency and the Los Alamos Scientific Laboratory jointly sponsored a summer study on high-altitude nuclear weapons effects. One of the working groups formed during the study addressed issues concerned with satellite link survivability in nuclear environments. This report is a brief summary of the report of the Mitigation Techniques Working Group.

DNA 4576T, *Phase Coherent Demodulation of Satellite Links Through a Nuclear Disturbed Channel* , R. Ibaraki, et al, ESLTM957, ESL Incorporated, February 1978

Satellite communication links using binary phase-shift-keying modulation may suffer severe performance degradation in the nuclear environment. The performance of both CPSK and DPSK demodulators is assessed by simulating the operation of generic receiver models with phase modulated signals that have been corrupted by a simulated nuclear environment.

DNA 4579T, *NAVSTAR Global Positioning System Errors in a Frequency - Selective Fading Nuclear Environment*, E. Tsui, et al, ESL-TM933, ESL Incorporated, February 1978

This report addresses the performance of the Magnavox "X-set" receiver code and various carrier loop configurations for a satellite link occluded by plasma striations resulting from a high-altitude nuclear exchange. A power-law fading nuclear channel was modeled and an efficient PN code correlation simulator was developed to determine the effects of a time-varying frequency-selective channel on code loop performance. The important fading channel effects impacting navigation system performance are found to be signal amplitude, phase, and time delay fluctuations.

DNA 4578T, *Propagation Effects on DSCS II Links*, R.L. Bogusch, et al. MRC-R-333, Mission Research Corporation, December 1977.

This report describes the results of the first phase of an investigation of the effects of propagation disturbances on DSCS II links in a nuclear environment. Objectives of this work are to determine the potential significance of signal disturbances on DSCS II performance and to identify methods of reducing the effects of propagation disturbances.

AFWL-TR-77-49 (AD C012 379L), *The Performance of AFSATCOM I Narrowband in Scintillated Environments*, L.A. Wittwer, Air Force Weapons Lab, September 1977

The performance of the AFSATCOM I narrowband model is calculated for strongly scintillated environments. The performance is in terms of message reception probabilities which, in turn, determine overall mission success.

DNA 4353T-1C (AD C015 217), *Transatlantic Satellite Link Survivability - Propagation Path Analyses*, R. Ibaraki and J. Marshall, ESLTM875, ESL Incorporated, August 1977

This report examines the survivability of specific transatlantic satellite links via the DSCS-II, NATO-IIIA, and INTELSAT IV-A satellites.

RDA-TR-106507-001, *Nuclear Effects Vulnerability of Future MILSATCOM Links* R&D Associates, June 1977

This document contains the proceedings of a two-day workshop on the Nuclear Effects Vulnerability of Future MILSATCOM Links. The workshop, held in May 1977, was organized by the Office of the Assistant Secretary of Defense for Command, Control, Communications and Intelligence with the following objectives: (1) to review the architectural framework within which future MILSATCOM systems may evolve; (2) to identify the significant sources of uncertainties in nuclear performance predictions at frequencies in and above the military UHF band that may directly impact MILSATCOM policy; (3) to make a prognosis concerning the possibility of reducing nuclear effects by changing system parameters to cope with known effects and/or changing system concepts to remove dominant effects and avoid model uncertainties.

This document contains a summary of key workshop conclusions in addition to the 13 papers presented at the workshop by invited speakers.

DNA 4259-T (AD C012 425), *The Global Positioning System Navigation Receiver Performance in a Nuclear Environment* , E. Tsui, et al, ESL-TM737, ESL Incorporated, November 1976).

An analysis of the GPS navigation receiver performance in a nuclear environment is presented. Emphasis is on providing a framework for understanding the impact of the nuclear environment on the GPS system navigation performance.

AFWL-TR-76-26 (AD C008 701L), *A Detailed Simulation of Message Communication Over a Specific SATCOM Link Under Disturbed Conditions* ', R.L. Bogusch and R.W. Hendrick, CSC-72M-196, Computer Sciences Corporation, November 1976

The effect of propagation disturbances on the ability to communicate information over a specific satellite communications link has been investigated in detail.

DNA 4158T (AD C012 653), *On Frequency-Hopping with Coding as a Nuclear Environment Mitigation Technique for Satellite Links* ', R.W. Ruky, et al, ES2TM773, ESL Incorporated, October 1976

This report presents results of an initial effort to categorize the radomization effectiveness of frequency-hopped M-ary FSK modulation techniques when the channel exhibits frequency selective fading.

AFWL-TR-76-25-3 (AD C008 700L), *Effects of Propagation Disturbances on a Specific Satellite Communications Link, Vol III: Calculation of Link Performance* R.L. Bogusch, MRC-R-156. Computer Sciences Corporation, November 1976

The first-order analysis of nuclear effects on communications signal propagation has been performed for a link involving a specific satellite and two airborne terminals. For this preliminary analysis, a specific link and mode of operation were selected for detailed investigation in a few nuclear detonation scenarios. The analysis consists of three primary areas of investigation: response of the communications receiver hardware to degraded signals, prediction of signal propagation disturbances in a nuclear environment, and detailed calculation of system performance in specific environments.

AFWL-TR-76-25-2 (AD B014 863L), *Effects of Propagation Disturbances on a Specific Satellite Communication Link, Vol II: Models of Propagation Disturbances*, R.L. Bogusch, MRC-R-156, Computer Sciences Corporation, October 1976.

AFWL-TR-76-25-1 (AD B014 862), *Effects of Propagation Disturbances on a Specific Satellite Communications Link, Vol I: Analysis of Hardware Response*, R.L. Bogusch, MRC-R-156, Computer Sciences Corporation, October 1976.

GE76TMP-52 (AD C009 788), *Satellite and Rocket System Performance Analyses* R.R. Rutherford and B. Gambill, General Electric—TEMPO, October 1976

An estimate is provided of nuclear weapon expenditures required to block the transmission of the EAM message from the National Emergency Airborne Command Post (NEACP) via several satellite systems and the Emergency Rocket

Communication System (ERCS). The satellite systems considered were AFSATCOM and SDS at UHF frequencies and LES 8 at K-band. Required performance, EAM message format, nuclear weapon effects, and modeling are discussed.

AFWL-TR-76-46 (AD B014 937L), *Propagation Effects on Satellite Systems: A Brief Status Report*, R.L. Bogusch, II/3-M-003, Computer Sciences Corporation, September 1976.

This report reviews the current state of knowledge and uncertainties in the area of nuclear detonation-induced ionospheric disturbances which affect uplink/downlink radio propagation for satellites. The treatment is primarily qualitative. Conclusions with regard to the relative importance of absorption and scintillation type effects are drawn. Recent progress and planned future efforts are described.

DNA 4011T-C-1 (AD C010 704), *PACOM Satellite Link Vulnerability Summary for Project APACHE* , J.M. Marshall and V.L. Mower, ESL-TM-756, ESL Incorporated, August 1976

DNA 4011T-C-2 (AD C011 058), *DSCS Link Vulnerability for Project APACHE*), V.L. Mower, et al, ESL-TM-753, ESL Incorporated, August 1976

DNA 4011T-C-3 (AD C011 581), *VHF SATCOM Link Vulnerability Analysis for Project APACHE (* , V.L. Mower and J.M. Marshall, ESL-TM-751, ESL Incorporated, August 1976

DNA 4011T-C-4 (AD C011 582), *INTELSAT Link Vulnerability Analyses for Project APACHE* ', V.L. Mower and J.M. Marshall, GSC-TM-572, ESL Incorporated, August 1976

As part of the DNA APACHE program, an analysis of the propagation path performance of the various operational and near-operational satellite communication links in the Pacific Theater has been undertaken for the APACHE nuclear scenario. The approach used in making the vulnerability assessment is to describe the link performance degradation both geographically and temporally on a map of the Pacific Theater. In addition, the performance of selected DCA links is simulated, showing typical received messages. Results presented in Volumes 2, 3, and 4 are summarized in Volume 1.

DNA 4106F (AD C009 542), *Selected Satellite Link Performance in a Nuclear Environment* , B. Adams, et al, Computer Sciences Corporation, August 1976

The performance of selected links of AFSATCOM II, DSCS III, and GPS has been parametrically derived for a fading (scintillation) environment such as may be encountered following high-altitude nuclear bursts.

AFWL-TR-75-89 (AD C004 780), *Nuclear Effects on Ultra High Frequency Propagation for AFWL Command and Control Communications (C^3) Alternative Concepts* ' . C.H. Humphrey, et al, Research and Development Associates, January 1976

An examination of various alternative means of communication which could be used to strengthen certain existing critical Air Force communication systems whose vulnerability is difficult to accurately assess and/or whose equipment is technically or economically unfeasible to harden. Alternative systems considered include large rocket repeater, small rocket repeater, rocket-launched balloons, aircraft-dropped balloons, and aircraft-launched drones.

ESL-TM642 (AD C004 554), *AABNCP Link Survivability Analyses - DSCS*), V. Mower, et al, ESL Incorporated, September 1975 (

This report presents an evaluation of the effects of signal scintillations on communication links through the DSCS satellite at the East Pacific location to the AABNCP resulting from two single-burst, high-altitude nuclear scenarios.

ESL-TM-640 (AD C004 547), *AABNCP Link Survivability Analyses - SURVSATCOM* R. Kirby, et al, ESL Incorporated, September 1975

This report presents an evaluation of signal scintillation on the proposed LES-8 and LES-9 report-back link in three high-altitude nuclear scenarios.

ESL-TM639 (AD C004 553), *AABNCP Link Survivability Analyses - AFSATCOM (Phase I)*), ESL Incorporated, September 1975 (

This report presents an evaluation of the effects of signal scintillations on communications links from the AFSATCOM (Phase I) satellites to the AABNCP in three high-altitude nuclear scenarios.

ESL-TM616 (AD C004 552), *AABNCP Link Survivability Analyses - DSP Down-link and Striation Modeling* (. V. Mower, et al, ESL Incorporated, August 1975

This report presents an evaluation of the effects of amplitude and phase scintillations on communication links from the DSP satellites to the AABNCP resulting from a set of three high-altitude nuclear scenarios.

DNA 3825F (AD C007 979), *INCA Propagation Path Effects Assessment for Satellite and Troposcatter Communications in the Tactical Theater* ( ), J. Marshall, et al, ESL-TM633, ESL Incorporated, August 1975

This report addresses propagation path disturbances produced by tactical nuclear weapons that may affect satellite and troposcatter communication systems. As part of the INCA program sponsored by DNA, the emphasis is on a preliminary assessment of the propagation path disturbances that may arise from the limited nuclear exchanges described by the Europe I and II scenarios.

DNA 3632T-1 (AD C004 994), *DSCS II Performance in a Nuclear Burst Propagation Environment*), B. Adams, et al, Computer Sciences Corporation, May 1975

DNA 3632T-2 (AD B009 764L), *DSCS II Performance in a Nuclear Burst Propagation Environment* , B. Adams, et al, Computer Sciences Corporation, May 1975.

The performance of the Defense Satellite Communications System Phase II (DSCS II) when the propagation medium is disturbed by nuclear detonations has been considered. Specifically, performance measures have been obtained for particular modems to be utilized in the planned digital phase shift keying (PSK) DSCS II. Both binary and quaternary PSK (BPSK and QPSK) modes were considered for coded and uncoded transmissions.

DNA 3529T (AD C002 372), *Noncoherent PSK Satellite Communication Systems in a Nuclear Environment* V.L. Mower, et al, ESL-TM 504, ESL Incorporated, September 1974 (

This report describes nuclear weapon effects on differentially-coherent phase-shift-keying (DPSK) and noncoherent M-ary direct sequence spread-spectrum phase-shift keying (PN-NCPSK) satellite communication links. The effects of random phase scintillation, ionosphere signal dispersion, and random signal fading are considered.

DNA 3322T (AD 530 547L), *A Compendium of Contemporary Communication and Navigation Satellite Systems and Scintillation Observations* J. Roberts, J.M. Marshall, and R.K. Stevens, ESL-TM 431, ESL Incorporated, January 1974

This report summarizes communication and navigation satellite system parameters with emphasis on those parameters which, together with the characteristics of the propagation medium, determine communication link performance. A summary of scintillation observations presented in DNA 3258T is also given.

DNA 3258T (AD 530 416), *A Review of Satellite Signal Scintillations — Observations and Research* R.K. Stevens, ESL-TM-421, ESL Incorporated, November 1973.

This report summarizes research concerning ionospheric scintillations in the natural environment. Sections describing scintillation effects, scintillation research, global occurrences of ionospheric scintillation and its correlation with other measurable geophysical parameters, current calculation models, and theoretical work on physical processes resulting in inhomogeneities are presented.

DNA 3289T (AD 530 531L), *PSK Satellite Communications Systems in a Nuclear Environment* J. Roberts, et al, ESL-TM 391, ESL Incorporated, October 1973 (

This report describes nuclear weapon effects on Phase Shift Keying (PSK) satellite communication links and provides many of the supporting analyses for results presented in DNA 3185H.

EFFECTS OF NUCLEAR WEAPONS ON SCATTER SYSTEMS

HANDBOOKS

DASA 1956-1 (AD 390 254L), *Nuclear Effects on Satellite and Scatter Communication Systems Selected Examples*, Defense Atomic Support Agency, October 1967

DASA 1956-2 (AD 394 007L, AD 395 137L), ***Nuclear Effects on Satellite and Scatter** Communication Systems (U), Volume 1: General Prediction Techniques for Satellite Systems,* July 1968; *Volume 2: General Prediction Techniques for Scatter Systems,* October 1968, Defense Atomic Support Agency

This handbook contains two parts. Part 1 (DASA 1956-1) describes the propagation effects of selected nuclear bursts on satellite and scatter communication systems. The examples illustrate the approximate duration and extent over which typical systems may experience difficulty. In addition to specific results, a brief tutorial description of the effects of nuclear bursts on radio wave propagation in natural environments is given.

Part 2 (DASA 1956-2) consisting of two volumes, describes the effects of nuclear bursts on the propagation of satellite communication systems (Volume 1) and troposcatter and ionoscatter communication systems (Volume 2). Techniques to model a relatively wide range of nuclear situations and to predict how these situations would degrade the communication systems performance are presented. These volumes provide a basic understanding of nuclear phenomenology and its interrelation with troposcatter propagation and propagation to satellites.

REPORTS

DNA 4595T (AD C015 973), *Effect of Low-Altitude Nuclear Explosions on Tropospheric Scatter Communications Links* R.C. Scott, MRC-R-391, Mission Research Corporation, April 1978

Effects of low-altitude, low-yield nuclear explosions on the performance of tropospheric scatter communication links are calculated using the SCATTR computer program. Limits in time and geographical position of the explosion and interference sources are determined, beyond which the effects of the selected set of explosions can be neglected.

DNA 3825F (AD C007 979), *INCA Propagation Path Effects Assessment for Satellite and Troposcatter Communication in the Tactical Theater* J. Marshall, et al, ESL-TM633, ESL Incorporated, August 1975 (

This report addresses those propagation path disturbances produced by tactical nuclear weapons that may affect satellite and troposcatter communication systems. As part of the INCA program sponsored by DNA, the emphasis is on a preliminary assessment of the propagation path disturbances that may arise from the limited nuclear exchanges described by the Europe I and II scenarios.

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APPENDIX

PROPAGATION ENVIRONMENT PRODUCED BY NUCLEAR BURSTS

The energy released by a nuclear explosion affects the electromagnetic properties of the atmosphere mainly by the ionization of air. An ionized region can change the amplitude, velocity, and direction of signals propagated through the region. Other effects of importance to communication systems include noise radiated from regions heated by the explosion and the scattering and attenuation of signals by particulate matter carried into the atmosphere after bursts that interact with the earth's surface.

A.1 ENERGY RELEASE AND ATMOSPHERIC MODIFICATIONS

A.1.1 General

The concept of "stopping altitude" is useful in understanding the interaction of weapon radiation with the atmosphere. The stopping altitude is the nominal altitude to which a given radiation from space will penetrate straight down into the atmosphere before losing most of its energy. Since the density of the atmosphere varies so rapidly with altitude (see Figure A-1), most of the energy is deposited in a relatively thin layer near the stopping altitude. Alternatively, radiation emitted below its stopping altitude will only penetrate the atmosphere a short distance before depositing its energy. The stopping altitudes for weapon outputs from a typical nuclear explosion are shown in Figure A-1.

Energy deposited in the atmosphere can dissociate, ionize, and heat the air. In regions where sufficient energy is deposited to significantly heat the air, the region undergoes hydrodynamic motion and the ionization within the region is

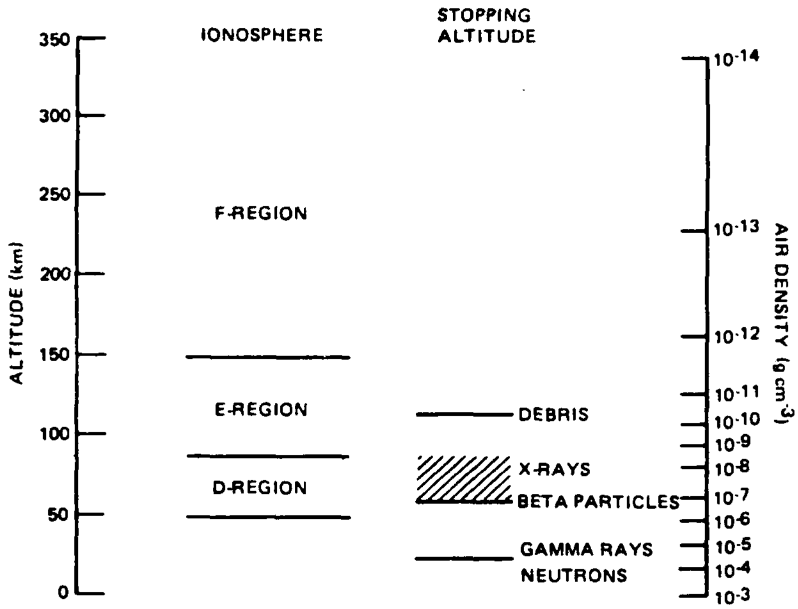

Figure A-1 Atmospheric properties.

determined by both hydrodynamics and atmosphere chemistry. Outside of heated regions the ionization produced by energy deposition is a strong function of deposition altitude. The lifetime of free electrons produced by prompt radiation varies from about 10^{-8} second at sea level to several minutes in the upper D-region. Electron lifetimes in the D-region are affected by solar conditions and are much shorter at night than in the daytime.

A.1.2 Fireball Region

For detonations below about 80 km, the X-rays are absorbed by the surrounding air, heating it to high temperatures and initiating radiative and hydrodynamic processes to form a relatively well defined region, termed the fireball, which is both highly heated and ionized. For detonations above about 80 km, the X-rays can escape to large distances; however, for detonations below about 300 km a significant fraction of the debris kinetic energy is converted to ultraviolet radiation, which still produces a fireball region. As the detonation altitude is increased above about 80 km, the Earth's magnetic field plays an increasingly important role in determining the debris motion and the deposition of debris kinetic energy. For detonations above about 500 km, the geomagnetic field is the dominant mechanism slowing the debris expansion.

The initial fireball size varies from a few tenths of a kilometer to several hundred kilometers in radius, depending on the weapon yield and detonation altitude. After the fireball is formed, it rises and expands. Figures A-2 and A-3 show fireball center altitude above ground zero and the fireball horizontal radius for selected bursts. For detonations above about 80 km, the Earth's magnetic field significantly affects the fireball growth and shape (see fireball geometry sketch in Figure A-3), and the fireball bottom altitude is an important fireball altitude measure.

For bursts below about 80 km, the fireball can remain highly ionized and affect propagation for several minutes. For higher altitude bursts, significant ionization can persist longer and the ionization becomes structured into geomagnetic field-aligned filaments (striations) that can produce scintillation effects for tens of minutes or longer, depending on burst, atmosphere, and propagation parameters.

The location of the fission debris, which is the source of long-lasting D-region ionization due to delayed radiation, is generally determined by fireball motion at early times. For bursts above several hundred kilometers, some debris may jet along and across geomagnetic field lines and be widely dispersed. At late times (hours) debris dispersal and location are largely determined by atmospheric winds.

A.1.3 Prompt Radiation

Ionized regions can also be produced outside the fireball by prompt and delayed radiation. The magnitude, spatial extent, and duration of these regions depend on burst height and weapon yield.

For detonations below about 80 km, most of the prompt radiation is deposited close to the burst point, producing the fireball discussed above. For higher burst altitudes, X-rays can produce widespread ionization in the D-region and X-rays and UV radiation can produce widespread ionization in the E- and F-regions.

In the D-region the electron density produced by prompt radiation decays as the electrons recombine with positive ions and attach to neutral particles to form negative ions. The electron density at a particular altitude is approximately given by

$$N_e(t) \approx \frac{N_e(o)}{1 + \alpha N_e(o)t} \; \frac{D + Ae^{-(A+D)t}}{D + A} \quad ,$$

where

$N_e(o)$ = electron density produced at t = 0

α,A,D = reaction rate coefficients that describe electron recombination, attachment, and detachment respectively

t = time after burst (seconds).

Note that the electron density will be independent of the initial ionization when

$$\alpha N_e(o)t \gg 1 \quad .$$

Since α is greater than about 3×10^{-7} in the D-region, all sources that produce at least 3×10^{6} electrons cm^{-3} are equivalent by about 1 second. This condition is defined as saturation and can be produced over widespread regions by relatively small yield, high-altitude bursts. The prompt D-region ionization decays to ambient levels by a few tens of minutes or less, depending on altitude and time of day.

Significant electron densities can also be produced in the E- and F-regions for several minutes or longer following prompt energy deposition. For large-yield bursts detonated above about 100 km, X-ray energy will heat the atmosphere below the burst sufficiently to cause upward motion of the air (referred to as atmospheric heave), changing the atmospheric density and composition at higher altitudes. This phenomenon can affect electron lifetimes in the E- and F-regions and affect the formation and dynamics of fireballs produced by subsequent detonations.

While most of the prompt energy is deposited in the burst locale, some of the energy can be transported to great distances. A neutron escaping the atmosphere has a half-life of about 12 minutes for spontaneous disintegration into a proton, an electron, and a neutrino. The electron (beta particle) is constrained to follow the geomagnetic field lines, eventually depositing its energy in the D-region. Since the neutrons can reach great distances before disintegrating, beta particles can be injected on geomagnetic field lines far from the burst and can cause ionization at distant points. For nuclear bursts detonated above about 100 km, some of the photoelectrons produced by X-ray energy deposition can escape the burst region and travel along geomagnetic field lines to deposit energy in the conjugate region.* The non-local prompt ionization sources are primarily of interest in analysis of nuclear test data and nuclear burst diagnostics, but may in some circumstances affect propagation in and below the HF band.

A.1.4 Delayed Radiation

Delayed radiation is the major source of persistent ionization outside the fireball. Even though it is a small fraction of the total weapon radiation, it can result in electron and ion densities well above ambient concentrations. The location of the fission ebris determines where the delayed radiation effects will be observed. For debris altitudes below about 25 km, delayed gamma rays will deposit their energy close to the debris. Because of the relatively short electron lifetimes (large electron loss rates), significant electron densities require large en gy depositions.

For debris altitudes above about 25 km, gamma rays can penetrate large distances through the atmosphere. If radial spreading of the gamma rays is neglected, the maximum energy deposition occurs close to the gamma ray stopping altitude (approximately 25 km). However, the maximum electron density generally occurs at higher altitudes in the D-region, where the electron lifetimes are larger (electron loss rates smaller). Close to the debris region, the energy deposition and resulting electron density can be large due to the high gamma ray flux levels.

For debris altitudes below about 60 km, beta particles deposit their energy within or close to the fission debris region. At higher debris altitudes, beta particles can travel large distances through the atmosphere; however, because they are charged particles (high-energy electrons) they spiral along the Earth's magnetic field lines, depositing most of their energy at approximately 60-km altitude. For debris regions above about 80 km, about half of the beta particles deposit their energy in the burst locale and about half deposit their energy in the conjugate region. Beta particles are more efficient than gamma rays in producing persistent electron density, because they are confined by the geomagnetic field and deposit most of their energy in a region of relatively long electron lifetimes.

Non-local energy deposition can produce distant, low-level ionization. Compton electrons produced by gamma rays above about 70 km can escape the atmosphere and follow geomagnetic field lines to the conjugate region. Also, photons produced

*The conjugate region is the region in the opposite hemisphere that is defined by following the geomagnetic field lines from the burst locale.

by beta particle energy deposition (beta bremsstrahlung) can produce widespread ionization in the conjugate region. As for the non-local prompt sources, the ionization is primarily of interest in diagnostics and propagation effects in and below the HF band.

A.2 (GENERAL PROPAGATION EFFECTS

Changes in the amplitude and phase of an electromagnetic wave can be described in terms of the index of refraction of the medium through which the wave propagates. Changes in the index of refraction can result in absorption, refraction, time delay (change in propagation velocity), dispersion, Doppler frequency shifts, Faraday rotation, scatter, and scintillation. In terms of communication and navigation system performance, these effects result in signal reduction and distortion and position and velocity errors.

The heated region from a nuclear burst (the fireball) is also a strong, frequency-dependent, thermal noise emitter. The received system noise will increase if the beam intersects the fireball, thus reducing the signal-to-noise ratio. (U)

Surface or near-surface bursts can loft large masses of particulate material (dust, rocks, etc) into the air. This material can absorb and scatter electromagnetic radiation.

A.2.1 (Absorption

Absorption is the major cause of signal attenuation in a nuclear environment. It results from the collision of free electrons set in motion by the electromagnetic wave with other particles. Generally absorption occurs in or below the D-region and is proportional to the electron and neutral particle density. Absorption can occur in the E- and F-regions, where the neutral particle density is low, if the electron density is high enough to cause the electron collision frequency with ions to become important.

For ionization regions below about 20 km, absorption is relatively insensitive to the propagation frequency. In the D-, E-, and F-regions, absorption scales inversely with the square of the frequency.

A.2.2 (Refraction

An electromagnetic wave propagating into an ionized region will have part of its energy reflected from the boundary and part transmitted across the boundary. The transmitted wave changes direction at the boundary and is bent (refracted) away from the region of low refractive index. The bending is proportional to the gradient of the refractive index normal (perpendicular) to the direction of propagation.

Refraction results in angular measurement errors. Also, if more than one propagation path can exist between two points (due to refraction or reflection), there can be multipath interference, resulting in large signal fluctuations as the individual signals combine with changing relative phases.

Refraction in the D-region caused by nuclear-burst-produced ionization is normally accompanied by large absorption. However, significant refraction may occur when the propagation path passes close to the fireball or close to regions ionized by beta particles (particularly when the propagation path is nearly parallel to the Earth's magnetic field lines). In the E- and F-regions, where the electron collision frequency is small, electron densities sufficient to change the direction of propagation by a few degrees can occur without causing significant absorption.

A.2.3 Velocity of Propagation (Time Delay)

In an ionized region, the velocity associated with the transmission of energy is less than in vacuum, and the time required for a signal to propagate a given distance is increased. Typical values of time delays associated with ionization caused by nuclear bursts range from a few nanoseconds to a few tens of microseconds. This can result in range errors from meters to a few kilometers. The larger time delays are usually accompanied by significant absorption when the ionized region occurs below 100 km. The propagation time delay is directly proportional to the integral of the electron density along the propagation path and inversely proportional to the square of the frequency.

A.2.4 Dispersion

The phase velocity in an ionized region (dispersive medium) is frequency dependent. Therefore, the phase relation among various portions of the signal that are transmitted at different frequencies will be modified. This will cause a stretching and smearing of the received waveform. The significance of dispersion depends critically on the type of signal propagated and the signal processing employed. For frequency division multiplex systems, dispersion can result in interchannel interference. Pulse systems will suffer reduced signal strengths if the pulse shape is significantly distorted. Dispersion effects below 100 km appear to be negligible in comparison to absorption. At higher altitudes, burst-produced ionization may cause important dispersion effects, but only for wide-band signals (bandwidths of the order of 1 percent or more of the carrier frequency) and probably only for propagation through fireball regions after the electron density has decreased sufficiently so that absorption is not overriding.

A.2.5 Doppler Frequency Shifts

A time-dependent phase change is equivalent to a carrier frequency shift. Since the phase changes are proportional to the electron density integral along the propagation path, frequency changes may be caused by electron density changes along a fixed propagation path or from motion of the propagation path in a region of inhomogeneous electron density. For a fixed propagation path, frequency changes caused by nuclear-weapon-produced ionization are small (a few hertz for a 10-MHz signal) by a few seconds after burst. Larger frequency changes may occur when the propagation path moves through regions of high electron density such as the fireball; however, then absorption generally will be more important.

A.2.6 Faraday Rotation

Another effect to be considered is change in the polarization (spatial orientation of the electric field) of a wave traversing an ionized medium in the presence of an external magnetic field. The polarization change, called Faraday rotation, is proportional to the integral of electron density along the propagation path and the Earth's magnetic field strength, and depends on the angle between the direction of propagation and the magnetic field. Faraday rotation can affect the received signal strength for systems using linearly polarized signals.

A.2.7 Scatter and Scintillation

Inhomogeneities in the dielectric constant of the propagation medium can cause some of the incident energy to be scattered or reflected away from the original propagation direction. The direction of scatter depends on the shape of the inhomogeneities and the orientation of the incident beam. Energy that is forward scattered as the wave traverses inhomogeneous regions can cause fluctuations in the amplitude and phase of the wave, called scintillation. Propagation through magnetic-field-aligned ionization in late-time, high-altitude fireballs and possibly in disturbed portions of the E- and F-regions outside of fireball regions may produce significant fluctuations in the phase, amplitude, time delay, and angle of arrival of the signal. The nuclear scintillation effects are analogous to the twinkling of stars as seen through the Earth's atmosphere. However, in the nuclear case the phase fluctuations can be several orders of magnitude larger than for the natural case.

A.2.8 Other Effects

In addition to the effects described above, nuclear bursts produce several other effects that can be of importance to system operation. Among these are thermal radiation, synchrotron noise, bremsstrahlung, and particle scatter and obscuration caused by material carried up by surface or near-surface bursts.

The received noise level can be increased by thermal emissions from fireball regions. The fireball may remain at temperatures above about 1000 K for a few hundred seconds and may produce effective antenna noise temperatures of several thousand degrees if the antenna is pointed at the fireball. In general, thermal noise will be significant only for systems with low receiver noise temperatures. The actual noise received will depend on the properties of the fireball (whether it is absorbing at the frequency of interest), the amount of attenuation outside the fireball, and the directivity of the antenna.

Synchrotron noise is produced by beta particles spiraling along the Earth's magnetic field lines. As a result of the spiral motion, the electrons radiate electromagnetic energy. However, the magnitude of this "noise" is generally not significant for frequencies above the VHF band.